AD-A104 671 ARCTEC INC COLUMBIA MD F/G 13/2
STUDY OF ICE CLOGGED CHANNEL CLEARING PROBLEMS.(U)
MAY 81 J W ST. JOHN, J L COBURN, T V KOTRAS DTCG38-80-C-80039
UNCLASSIFIED 569C-5 USCG-D-34-81 NL

1 OF 3
AD A
104671

LEVEL

AD A104671

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
USCG-D-34-81	AD-A104 671	

4. Title and Subtitle	5. Report Date
STUDY OF ICE CLOGGED CHANNEL CLEARING PROBLEMS	May 1981
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
J. W. St. John, J. L. Coburn, T. V. Kotras	569C-5
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
ARCTEC, Incorporated 9104 Red Branch Road Columbia, Maryland 21045	11. Contract or Grant No. DTCG38-80-C-80039
	13. Type of Report and Period Covered Final Report Feb. 1980 - May 1981
12. Sponsoring Agency Name and Address United States Coast Guard Research and Development Center Avery Point Groton, Connecticut 06340	14. Sponsoring Agency Code CGR&DC 17/81

15. Supplementary Notes

16. Abstract

This study develops a mathematical model for the simulation of ships transiting a river under brash ice conditions. The model predicts the growth of the ice on the St. Marys and St. Lawrence Rivers and the subsequent transit times and delays of the ships at traffic levels predicted for the year 2000. Ice removal has been incorporated in the model and various ice removal strategies and removal rates have been investigated.

The results of the removal rate study are presented as well as several preliminary studies that document the evolution of the project. Brash ice removal rates are chosen for the conceptual design of removal systems for the St. Marys and St. Lawrence Rivers.

Removal concepts to meet these removal rates are screened and the better concepts are developed into designs. Estimates of acquisition costs are made and operational parameters are developed to the point where operational costs could be determined.

17. Key Words	18. Distribution Statement
Great Lakes Shipping Winter Navigation Ice Growth Ice Removal Simulation, St. Lawrence Seaway	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	272	

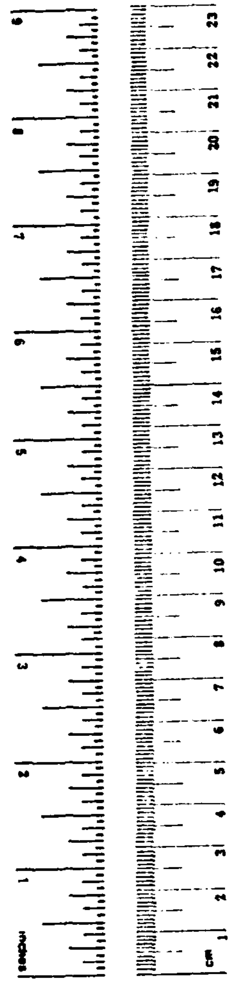
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

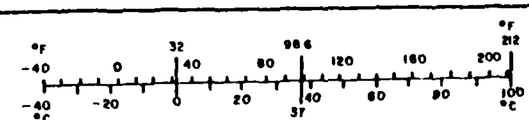


TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (cont'd)

LIST OF TABLES (cont'd)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

1. SUMMARY

This study develops a mathematical model for the simulation of ships transiting a river under brash ice conditions. The model predicts the growth of ice on the St. Marys and St. Lawrence Rivers and the subsequent transit times and delays of the ships at traffic levels predicted for the year 2000. Ice removal has been incorporated in the model and various ice removal strategies and removal rates have been investigated.

The results of the removal rate study are presented as well as several preliminary studies that document the evolution of the project. Brash ice removal rates are chosen for the conceptual design of removal systems for the St. Marys and St. Lawrence Rivers. Removal on the St. Marys River should be limited to removal in the four turns, Striblings Point, Mirre Point, Johnson Point, and Winter Point, at a combined removal rate of 50,000 ft^3/day. Removal can be delayed until ice thicknesses reach approximately 31 inches. Systems on the St. Lawrence River should be designed to a removal rate of 37,000 ft^3/mile-day and 30 inches of ice can be allowed to form before removal begins.

Removal concepts to meet these removal rates are screened and the better concepts are developed into designs. Estimates of acquisition costs are made and operational parameters are developed to the point where operational costs could be determined.

Two designs for the St. Marys River and one design for the St. Lawrence River should be considered in detail. Operational costs should be developed for these Alternatives so that life-cycle costing can be evaluated. The Alternatives are:

1. A WTGB transits the four turns of the St. Marys River each day making approximately 2 ice collection "loads" per turn. The WTGB has a plow that it uses to push a large volume (6400 ft^3/load) of brash ice to ice collection conveyors mounted on a barge near the middle of each turn. The WTGB must feed its load to the conveyors. The conveyors remove the ice from the water and transfer it to a long conveyor mounted on pilings. The ice is transported several hundred feet while being elevated to dump on a storage pile in shallow water.

2. An AST (Archimedean Screw Tractor) transits the four turns of the St. Marys River in a 24 hour operating day. At each turn, brash ice is scooped from the turn and dumped over an ice boom along the outside of the turn. The AST uses a front-end loader type bucket to lift and transport the ice. The vehicle would work its way around one turn and then proceed to the next turn.

3. A barge would be pushed down the length of the International Section of the St. Lawrence River, making one pass in 24 hours. The barge would house ice collection conveyors to scoop the ice from the water and a rotating boom conveyor to transfer the ice to the adjacent level ice cover. Ice would be removed at various points along the boom conveyor to provide an even distribution over 50 feet of the level ice on either side of the channel. Ice would be transferred to one side on an upbound passage and the other side on a downbound passage the next day.

The principal conclusion drawn from this study is that brash ice removal does appear to be effective and feasible at an acquisition cost of under $800K.

The entire study process was reviewed and the validity of the conclusions was found to depend upon:

1. The ice growth model
2. The ship performance model
3. The transit model
4. Several factors pertinent to specific designs:
    a. Ice piece size as far as need for icebreakers
    b. Capability of shorefast ice to support broken ice disposal along channel of St. Lawrence River
    c. The plow-performance of the WTGB
    d. The design feasibility of the AST in a loader configuration
    e. The feasibility of successfully applying the transfer techniques described (conveyors, etc.).

Confidence in the overall conclusions is a function of uncertainty in the factors identified above. The following recommendations are focused at reducing these uncertainties and therefore enhancing confidence and eventual successful implementation.

Recommendation 1

The revised traffic projections from other studies should be reviewed with regard to their impact on this study.

Recommendation 2

The brash ice growth model should be validated with a controlled experiment in a particular reach by simulating high traffic levels with a frequent transit of a Coast Guard icebreaker. The brash ice thickness should be monitored along with meterological data. The ice growth model can then be "tuned" to provide validated results. This experiment can be coordinated with other related experimental objectives.

Recommendation 3

A study of piece size is recommended to be included with the high traffic brash ice thickness study described above.

Recommendation 4

The ice sheet's ability to support the broken ice must be verified by analysis and an experiment. It is recommended that an analytical approach be employed using whatever data are available.

Recommendation 5

A comprehensive model test program is recommended to determine the WTGB's performance in brash ice with a plow. It will be necessary to first complete a careful analysis of the phenomena involved to insure that proper modeling techniques are employed.

Recommendation 6

It is recommended that a complete preliminary design of an AST, configured as a 3 ton loader,be developed. Detailed performance predictions and cost estimates should be included.

2. INTRODUCTION

The Winter Navigation Season Extension Demonstration Program [30]* has studied the technical feasibility of commercial ships operating on the Great Lakes-St. Lawrence Seaway (GL-SLS) System over the past nine years. In summary, that program concluded that it is technically feasible to extend the Navigation Season on the Great Lakes to a year-round basis and that season extension would be cost-beneficial to the nation. On the St. Lawrence River, however it was concluded that the technical feasibility of extending the navigation season to year-round could not be fully determined and required further study.

Of vital importance in realizing the potential benefits of extended season navigation on both the Great Lakes and the St. Lawrence Seaway is the ability of the commercial cargo ships to maintain transit times, along the various trade routes, close to summer season transit times. To accomplish this, certain ice control equipment must be located around harbors and in channels to minimize delays to shipping caused by the presence of ice. One of the major concerns in the shipping channels of the St. Marys River and the St. Lawrence Seaway is the build-up of brash ice, which has been judged as an impediment to commercial navigation in these major arteries. The rate of growth of brash ice in a shipping channel is greater than that of the level ice immediately adjacent to the channel because each passing ship breaks up the refrozen ice cover, mixes the ice into a jumble of solid ice pieces and water-filled voids, and brings more water to the surface where it can quickly freeze. This increased thickness of refrozen and unconsolidated brash ice increases the resistance a vessel must overcome in maintaining its forward velocity. Also, the presence of brash ice in turns decreases ship maneuverability because it generates large side forces which must be overcome for the vessel to negotiate the turns.

This study develops a mathematical model for the simulation of ships transiting a river under brash ice conditions. The model predicts the growth of ice on the river and the subsequent transit times and delays of the ships. Ice removal has been incorporated in the model and various ice removal strategies and removal rates have been investigated.

The results of the removal rate study are presented as well as several preliminary studies that document the evolution of the project. Brash ice removal rates are chosen for the conceptual design of removal systems for the St. Marys and St. Lawrence Rivers. Removal concepts are screened and the better concepts are developed into designs. Estimates of acquisition costs are made and operational parameters are developed to the point where operational costs could be determined. The conclusions drawn from this study as well as the recommendations for a course of action from this point are made in the last section.

---

* Numbers in brackets denote references in Section 11.

During this study, four interim reports were produced. There were numerous meetings where preliminary studies were shown to the U.S. Coast Guard and the discussion, clarification, and guidance led to further studies. The interaction with the U.S. Coast Guard, the guidance received, and the technical material from the interim reports have been combined in a logical fashion in this work.

3. DATA FOR SIMULATION MODEL DEVELOPMENT

3.1 Description of the Rivers

The St. Marys River, from the Soo Locks to Detour Passage, shown in Figure 3.1, is approximately fifty (50) miles long. There is a speed limit on most of the river so that the normal open water transit time is approximately four (4) hours. In the winter the west navigation channel around Neebish Island is presently closed to navigation and two-way traffic follows the east channel. This channel has a number of very tight turns, where vessels currently experience difficulty during heavy ice conditions. Characteristics of these turns can be found in Appendix A.

Figure 3.2 shows the entire International Section of the St. Lawrence Seaway extending from the head of the river at Lake Ontario to the U.S. - Canadian border downstream from Snell Lock. The length of the entire International Section is approximately 105 miles. From an examination of aerial photographs of the International Section of the St. Lawrence River during the winter and Lewis, et al [6], it is observed that open water areas exist in some stretches of the river for much of the winter. These open water areas include the following reaches of the river: upstream from Ogden Island to Iroquois Lock; from Cardinal to the Galop Island Ice Boom which crosses the channel at Galop Island; in the Brockville Narrows; and in the Upper Narrows near Alexandria Bay.

The St. Lawrence Seaway Demonstration Corridor runs for 20 miles from Morristown, New York to Cardinal, Ontario, as shown in Figure 3.3. Presently, the Demonstration Corridor is not navigable in the winter because of two ice booms which extend across the navigation channel: Ogdensburg Prescott Ice Boom located between Ogdensburg, NY and Prescott, Ontario; and the Galop Island Ice Boom located at the head of Galop Island. Modifications to these booms have been designed and tested in a physical hydraulic model to permit commercial navigation to traverse these boom locations for both limited extended season navigation and for year-round navigation [13]. With these modifications, the shipping channel would remain open from the Galop Island boom to Cardinal and for a mile or two below the Ogdensburg-Prescott boom. Eliminating the open water areas from consideration, the total length of potential ice clogged channels in the International Section of the St. Lawrence River is approximately 87 miles.

In the St. Lawrence River, it is important to note that channel clearing will probably not be sufficient to maintain winter navigation past Ogden Island due to the hanging dams of frazil ice which characteristically form there. These hanging dams have been measured in excess of 30 feet deep. As a result, additional ice control structures and/or river regulating strategies will probably be required to maintain winter navigation, even with effective channel clearing. For this current study, these additional structures and regulating strategies are beyond the scope of work.

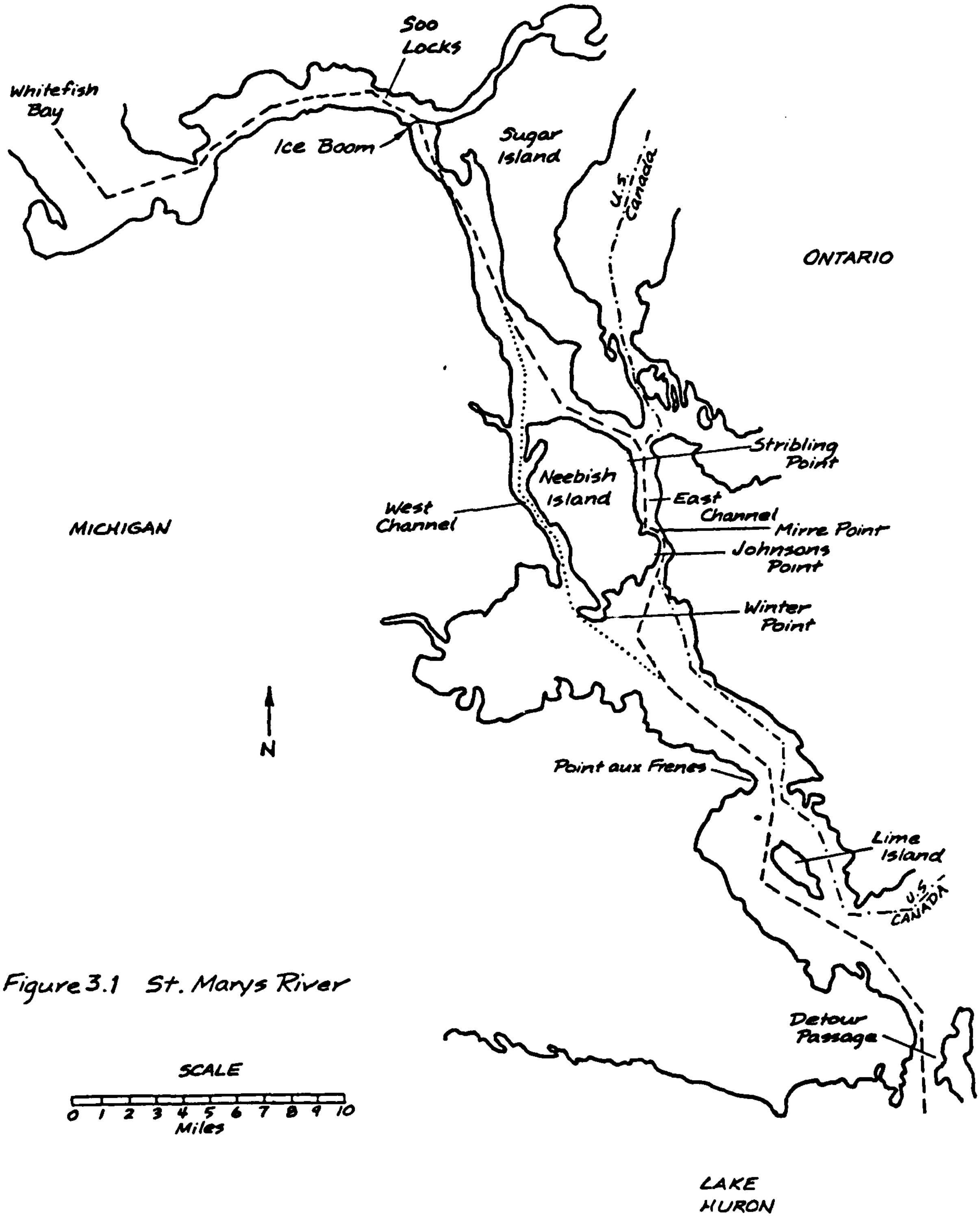


Figure 3.1 St. Marys River

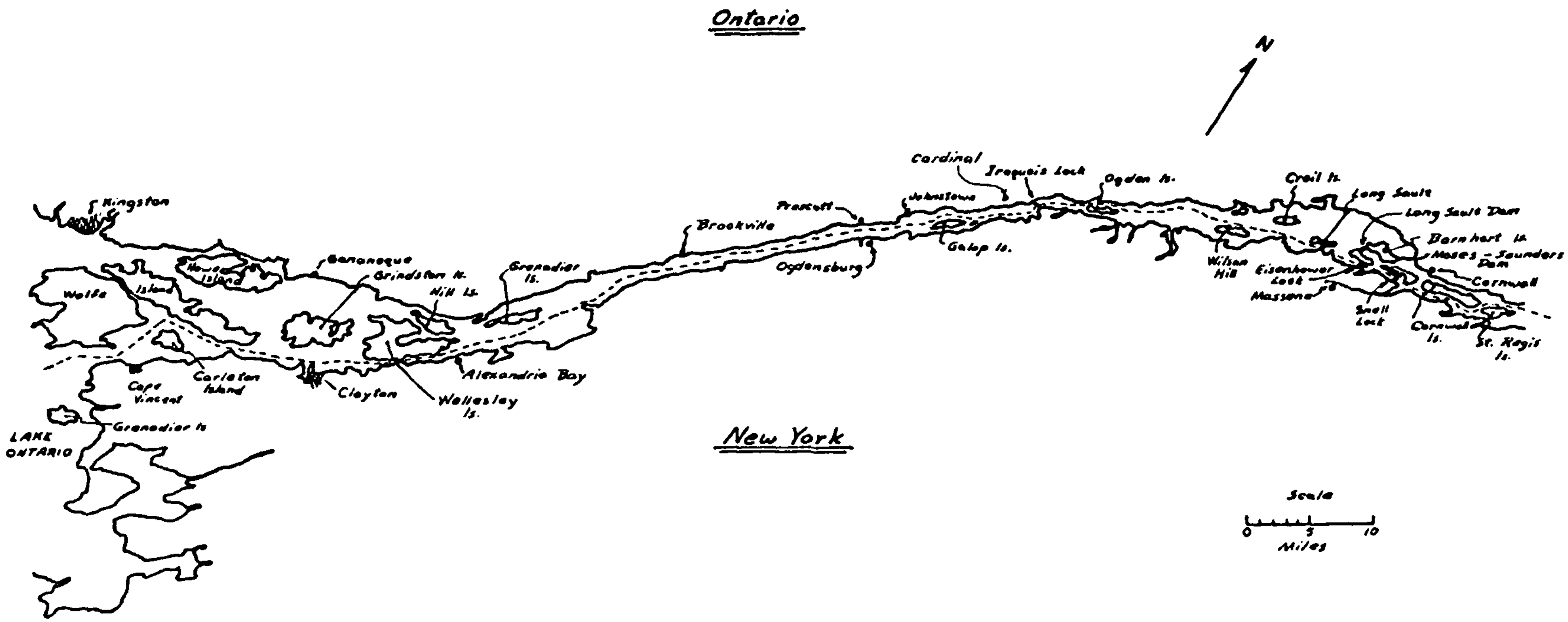


Figure 3.2 International Section of the St. Lawrence River

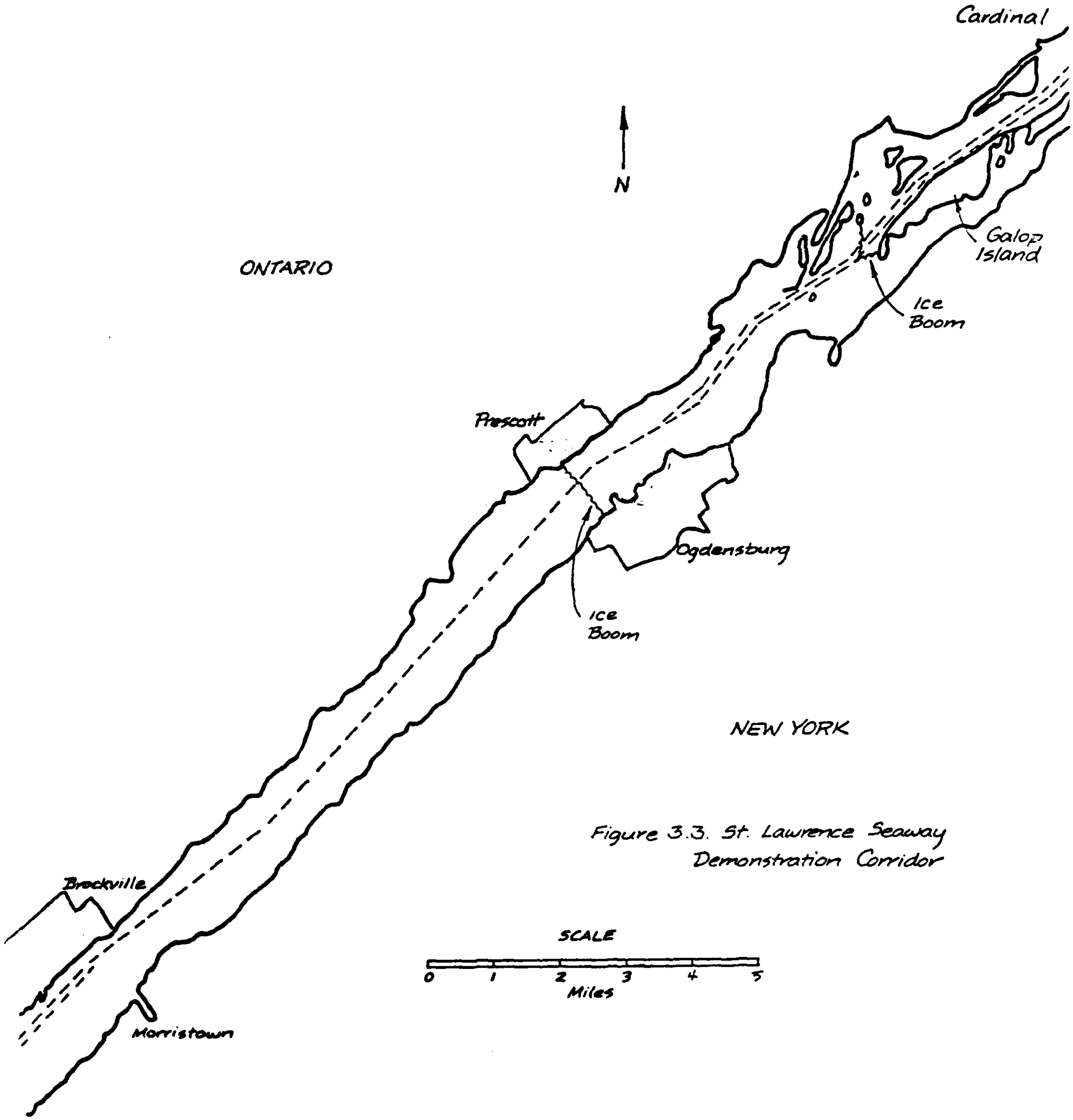


Figure 3.3. St. Lawrence Seaway Demonstration Corridor

3.2 Climatic and Hydrologic Data

Data was gathered to define baseline climatic and hydrologic conditions to be used in this study for the St. Marys and the St. Lawrence Rivers. More specifically, the weather data of primary concern, needed to estimate the thickness of brash ice in the navigation channel, were air temperature, wind speeds and directions, and river current speeds. A summary of the results of this task are presented in Table 3.1.

Using the available historical weather data listed in Table 3.1 records of cumulative freezing degree days, *FDD* were compiled for each of the associated winters defined as the period from 15 December to 31 March. From this compilation of freezing degree days, five (5) winters were selected, for each of the two study areas, to correspond to the following levels of winter severity: severest, mildest, average or mean, average plus one standard deviation (colder), and average minus one standard deviation (milder). These winters, along with their associated cumulative freezing degree days are listed in Table 3.1. Plots of the cumulation of freezing degree days versus time of year for each of the selected winters are presented as part of the study of ice growth rates in Appendix C.

Again using the available historical weather data, the frequency distribution of wind speed and wind direction were determined for the selected years. The results of this analysis are presented in Appendix A. In summary, the maximum wind speed experienced during the winter months in both study areas never exceeded 30 mph with prevailing winds from either a northwesterly or easterly direction for the St. Marys River. For the purposes of this study, a design wind speed of 50 mph in the direction parallel to that of the study area is used to account for high winds of relatively short duration.

Based on published data, river current velocities in the St. Marys River can range from 1.5 fps to 3.0 fps [28]; and in the St. Lawrence River, the river current velocities can range from less than 1.0 fps to 4.0 fps [13,27].

Information is also needed on ice growth conditions. A section discussing the ice growth and porosity coefficients used is presented in Appendix A.

TABLE 3.1 BASELINE CLIMATIC AND HYDROLOGIC CONDITIONS

Weather Station:	Sault Ste. Marie, Michigan		Massena, N.Y.	
Available Years of Data:	1962-1979 (Daily Basis)		1953-1979 (3-Hour Basis)	
Maximum Wind Speed*:	30 mph		30 mph	
Winter Severity:	YEAR CHOSEN	CUMULATIVE FREEZING DEGREE DAYS (°F-Days)	YEAR CHOSEN	CUMULATIVE FREEZING DEGREE DAYS (°F-Days)
Severest	1962-63	2059	1969-70	1665
Colder	1976-77	1751	1967-68	1517
Average	1967-68	1630	1968-69	1376
Milder	1963-64	1370	1965-66	1122
Mildest	1965-66	1245	1952-53	705
River Current Velocity:	1.5-3.0 ft/sec [28]		<1.0-4.0 ft/sec [13,27]	

*During the course of this study, a design wind speed of 50 mph in the direction of the river is used to account for high wind of relatively short duration.

3.3 Vessel Mix and Traffic Level Data

Predictions of ship transit frequency for the year 2000 have been made for both the St. Marys River and the St. Lawrence Seaway [10]. Table 3.2 lists the traffic levels for the half-month periods used in this simulation. On the St. Marys River, four traffic levels were investigated to determine sensitivity to the transit frequency. Traffic level 1 represents the predicted transits per day in the year 2000 for a ten month shipping season as proposed by the Lake Carriers Association. Traffic level 2 represents the transits per day for a twelve month shipping season. Traffic levels 3 and 4 are half the transits per day of traffic levels 1 and 2, respectively. These levels were included to determine the sensitivity of the channel clearing requirement to large changes in the traffic level. Only an eleven month shipping season was considered in the St. Lawrence Seaway because the locks, which are in series, must be closed for a month for annual maintenance. The traffic level for the Seaway was not varied because the results from the St. Marys River were not very sensitive to the variation in traffic level as long as the traffic level remains at a reasonable level (see Appendix C).

Table 3.3 lists the characteristics of typical ships that can be expected to use the St. Marys River in the winter by the year 2000 A.D. The 1000' Laker is judged as being one of the most capable ice transiting vessels operating in the St. Marys River in the winter (with the exception of the high-powered salties if season extension exists on the St. Lawrence River). The 640' and 730' vessels are less powerful ships and are less capable of transiting an ice clogged channel than the 1000' Laker. These vessels span the range from the least to most capable ice transiting ships that can be expected to transit the St. Marys River in the winter.

Table 3.4 lists the characteristics of typical ships that can be expected to use the St. Lawrence River in the winter by the year 2000 A.D. The 7200 SHP 730' Laker is the least capable ship allowed to use the St. Lawrence Seaway locks after December 12 according to the current Seaway Transit Restrictions (Appendix A) which prohibits vessels with an *SHP/LENGTH* of less than 9.8 from transiting upbound. The Salty listed in Table 3.4 is the most capable ship likely to navigate the St. Lawrence River.

3.4 Ice Specifications

The rationale and selection of ice specifications is presented in Appendix A. An ice piece size of 3 feet maximum dimension is chosen for use in this study based on a survey of the available literature. Ice mechanical and physical properties are determined in Appendix A as well.

TABLE 3.2 NUMBER OF SHIPS PER DAY TRANSITING THE ST. MARYS RIVER AND THE ST. LAWRENCE SEAWAY IN 2000

	PERIOD						
	Late Dec.	Early Jan.	Late Jan.	Early Feb.	Late Feb.	Early Mar.	Late Mar.
ST. MARYS RIVER							
Traffic Level 1	44.0	28.3	28.3	0.0	0.0	0.0	0.0
Traffic Level 2	40.6	25.6	25.6	24.0	24.0	23.9	23.9
Traffic Level 3	22.0	14.2	14.2	0.0	0.0	0.0	0.0
Traffic Level 4	20.3	12.8	12.8	12.0	12.0	12.0	12.0
ST. LAWRENCE RIVER	18.0	17.4	17.4	17.6	17.6	0.0	0.0

TABLE 3.3 VESSEL CHARACTERISTICS FOR THE ST. MARYS RIVER

VESSEL CLASS		5	7	10
LENGTH		640'	730'	1000'
BEAM		67'	75'	105'
POWER PLANT		Diesel	Diesel	Diesel
SHP		4000	8000	14000
OPEN WATER DESIGN SPEED		14.5 MPH	16.5 MPH	18.0 MPH
HULL SHAPE COEFFICIENTS	μ_0	5.56	5.56	5.56
	η_2	1.94	1.94	1.94

TABLE 3.4 VESSEL CHARACTERISTICS FOR THE ST. LAWRENCE RIVER

VESSEL CLASS	7	7	Salty
LENGTH	730'	730'	709'
BEAM	75'	75'	75'
POWER PLANT	Diesel	Diesel	Diesel
SHP	7200	8000	12800
OPEN WATER DESIGN SPEED	16.5 MPH	16.5 MPH	17.3 MPH
HULL SHAPE COEFFICIENTS μ_0	5.56	5.56	2.06
HULL SHAPE COEFFICIENTS η_2	1.94	1.94	5.53

4. SIMULATION MODEL DESCRIPTION

An overview of the program is given in this section. An in-depth discussion of the theory used in each portion of the program is presented in Appendix B.

The program developed for this study consists of a main portion and seven subroutines (see flowchart, Figure 4.1). The purpose of the main program is to accumulate and organize the input data required for manipulation in the various subroutines. All data regarding ship traffic levels in the periods, ship type, waterway characteristics, and thrust coefficients are initialized in this portion. Temperature data is transformed into an array of freezing degree days for the various winters. Subroutine TTIME is then called to oversee the calculation of a delay time for each day.

TTIME calculates the last day of winter being considered and chooses the traffic level for each day under consideration. The subroutine calls ICEGRO for the new ice thickness and then SPEED for the average speed and subsequently calculates the transit time and delay. TTIME also determines whether or not a ship will get stuck.

ICEGRO calculates growth of consolidated and unconsolidated brash ice in a channel on a ship transit by ship transit basis. Removal rates are taken into consideration in this section. Several different user options allow removal only when certain conditions exist.

Subroutine SPEED is then called to oversee a speed calculation based on the ship characteristics and amount of each type of ice in the channel. THRUST calculates thrust as a function of velocity and RESIST calculates resistance as a function of velocity. SOLVE computes a steady-state velocity using coefficients of the second order fit of the speed and thrust curves.

OUTPUT is called by the main program to organize the accumulated data in a form easily comprehended by the user. Several different options allow partial output to be printed or output accumulation up to and including any specified day of the winter being considered.

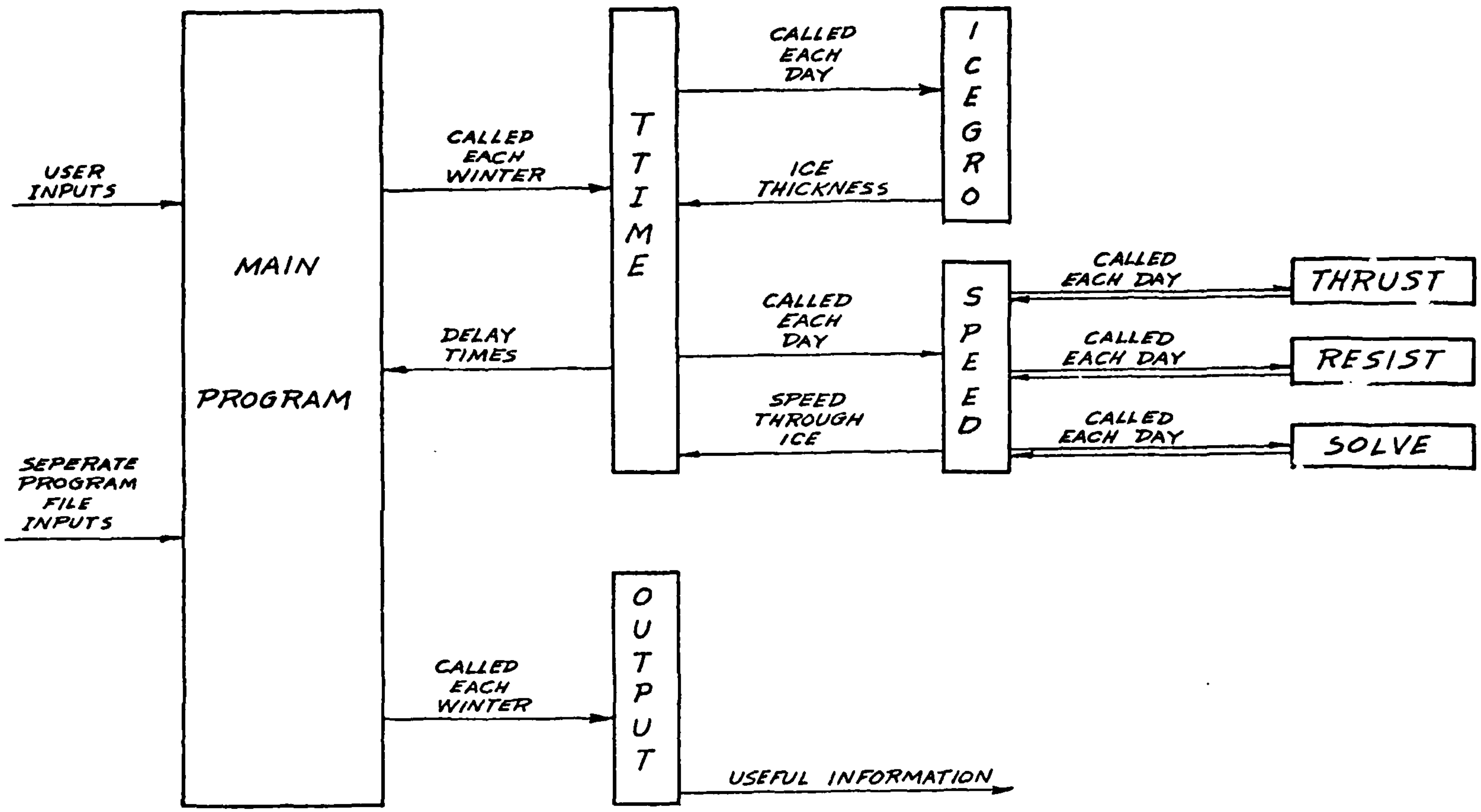


Figure 4.1. Flow Chart for Simulation Model for Brash Ice Growth Due to Ship Traffic on River

5. PRELIMINARY SIMULATION STUDIES

While the study was being done the mathematical model was being constantly updated and revised. Running a set of conditions in the model indicated new areas of development that should be considered. Those studies, which led to the final model and removal rate study, are presented in the Appendices.

Appendix C presents the results of the initial runs investigating ice growth and transit times. Only transit times in the straightaways for a 1000' Laker on the St. Marys River and a 730' Laker on the St. Lawrence River were investigated. A transit time validation study is presented in Appendix D. Actual ship transit data is compared with the model for 1976-77 winter on the St. Marys River.

From the study presented in Appendix C, the need for evaluating delay in the turns was established. In addition, more ship types were studied. The model was modified to account for the additional delay and new transit times were determined. The results are presented in Appendix E.

In all but the most mild winter, the Class 5 vessel will eventually exceed a delay of twelve hours due to its slow passage through the straightaways. In no case do the Class 7 and Class 10 vessels ever become stuck in the straightaways or exceed a delay of twelve hours due to slow speed in the straightaways. In all five winters the Class 5 vessel becomes stuck in the turns with no channel clearing, while the Class 7 vessel becomes stuck in the turns in the severe and colder winters. Twelve hours was chosen as a reasonable maximum acceptable delay for this study.

When the brash ice thickness exceeds 48 inches on the St. Lawrence River, the Class 7 Lakers may become stuck in the turn around Carleton Island. In the absence of channel clearing, the Class 7 Lakers become stuck in all but the most mild winter. The Class 7 Salty will become stuck in the turn late in the severe winter only.

Appendix F presents a biweekly removal rate study for the model as developed in Appendix E. Removal in the straightaway of the St. Marys River to permit continuous transit by Class 5 vessels is calculated. The removal rate in the four turns to permit transit with twelve hours of delay for Class 5, 7, and 10 vessels is also calculated. Removal will be restricted to the turns, since it is unlikely that many Class 5 vessels will be operating in the year 2000 [5]. A summary of the required removal rates is shown in Table 5.1.

Appendix F also presents required removal rates for a 730' Laker with 7200 SHP, the least capable ship operating on the St. Lawrence, for a variety of maximum delay times. These results are summarized in Table 5.2. The nine hour maximum delay was chosen for the follow-on studies.

TABLE 5.1 DAILY AVERAGE VOLUMETRIC ICE REMOVAL RATES

ST. MARYS RIVER

MAXIMUM ICE REMOVAL RATE TO MAINTAIN A MAXIMUM ALLOWABLE DELAY OF 12 HOURS

LEAST CAPABLE VESSEL	STRAIGHTAWAYS 10^6 ft^3/day	STRAIGHTAWAYS 10^3 ft^3/mile-day	JOHNSONS POINT 10^3 ft^3/day	STRIBLING POINT 10^3 ft^3/day	WINTER POINT 10^3 ft^3/day	MIRRE POINT 10^3 ft^3/day
Class 5 4000 SHP	2.17	43.5	82.6	105.6	101.9	67.8
Class 7 8000 SHP	0	0	49.6	63.4	61.2	40.7
Class 10 14000 SHP	0	0	46.1	59.1	58.9	37.9

TABLE 5.2 INTERNATIONAL SECTION OF THE ST. LAWRENCE RIVER

MAXIMUM ALLOWABLE DELAY	MAXIMUM ICE REMOVAL RATE 10^6 ft^3/day	10^3 ft^3/mile-day
6 hrs	7.81	90
9 hrs	5.90	68
18 hrs	4.34	50
24 hrs	4.08	47

Least Capable Vessel = Class 7 Laker, 7200 SHP

At this point, there was concern about the validity of using a biweekly time period to predict removal rate. Another study, presented in Appendix G, was done to examine the differences between daily and biweekly prediction of ice growth. The conclusions of this study were that the biweekly method predicted the average daily growth rate, the ice thickness and the removal start date well, but it was insensitive to the daily fluctuations in growth rate which were large. Since a design removal rate would be based on the peak growth rates, the daily method was chosen for the final removal rate study of Section 6.

6. REMOVAL RATE STUDY

The conclusions drawn from the numerous preliminary studies of Section 5 led to final refinement of the mathematical model and an approach to a parametric study of removal rates for the St. Marys and St. Lawrence. Unlike the previous studies, the removal rate and the ice thickness when removal starts are input to the model. The removal rate for any concept is constant, therefore, which more closely simulates an actual channel clearing system of fixed capacity. By keying removal to a certain ice thickness, a much more flexible and realistic model is obtained. If the limiting ice thickness is set to zero, ice will only be removed if there is enough ice to remove in a given day, but if the limiting thickness is set to the thickness just before ships start to get stuck, conditions similar to the preliminary studies can be examined. All limiting ice thicknesses in between can, of course, be determined as well.

The rationale, then, of this study was to take a much broader look at the possible removal strategies with the objective of reducing the required removal rate by the biweekly analysis of Appendix G. It was shown in Appendix G that the daily growth rates fluctuate drastically and a biweekly analysis couldn't follow those fluctuations. Also, it was felt that a removal program that started early in the winter could flatten the peaks and substantially reduce the required removal rate.

The assumptions for this study are as follows:

- All runs are done on a daily basis.
- Ice is removed if the ice thickness at the start of a day exceeds the amount to be removed for that day for either positive or negative freezing degree days.
- Ice is removed in the first quarter of a day evenly over an integer number of ship transits (6-hour removal in an 8 hour work day).
- Ship transits are equally spaced in a day.
- Delay is calculated as the days stuck plus the fraction of a day delayed when the river opens and a transit can be made.

The results of this study for the St. Marys River are presented in Figures 6.1 through 6.5. Since this analysis is a parametric study varying removal rate and the point at which removal starts, the conditions of input do not at all guarantee that the ships will not get stuck in a given winter. The number of days ships will be stuck and the average hours ships will be delayed are output as measures of merit of a particular removal strategy (combination of a rate and an ice thickness when removal starts.) Figures 6.1 to 6.3 plot average ship delay hours versus removal rate for each of the previously defined winters (Section 3.2). For each plot, removal begins at a different ice thickness.

In severe winters, ships start to get stuck in the turns on the St. Marys River if the removal rate is low enough as indicated by the large increase in average ship delay hours in Figures 6.1 to 6.3. Since delays in the straightaways do not amount to many hours, even in severe winters, a *minimum* removal rate that is acceptable from a delay point of view will be found by examining the area where ships just start to get stuck. Ships only get stuck in severe winters (assuming a 730 foot 8,000 SHP ship at the high traffic levels as is done in this study), so Figure 6.4 presents all the severe winters on one plot such that the curve of conditions where the ships start to get stuck can be seen. Figure 6.5 is a cross-plot of various interesting parameters versus ice thickness when removal starts, the variation of parameters along the dotted curve on Figure 6.4.

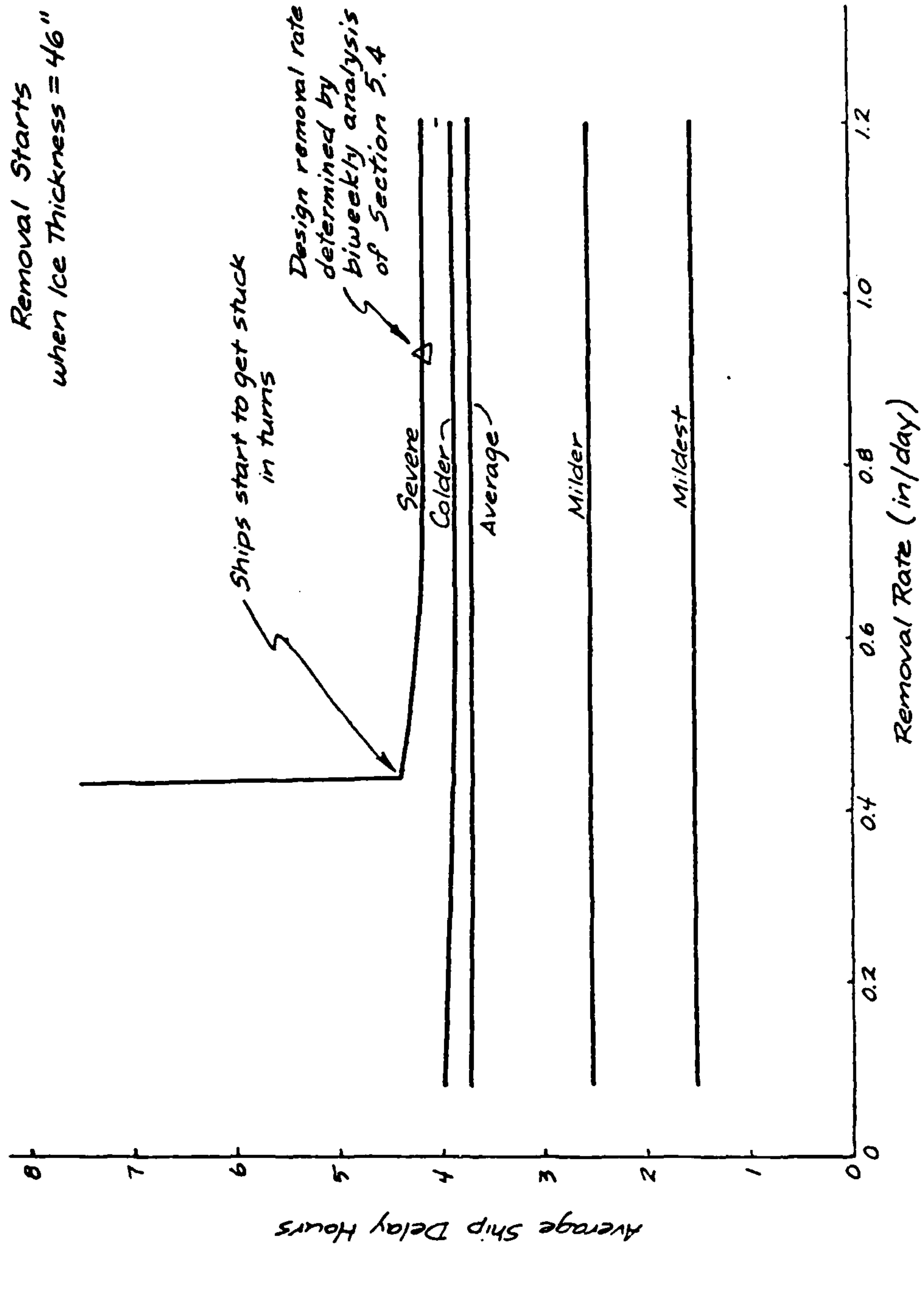
One can see in Figure 6.5. that average ship delay hours do not increase significantly. Removal rate remains relatively constant until the thickness at which ships start to become stuck is approached. The total amount of ice removed and the removal days (closely related) drop somewhat as the thickness when removal begins increases. These results are as expected. Removal rate is an indicator of acquisition cost and total amount of ice removed or removal days will largely determine operating cost. One can see from Figure 6.4, that a minimum cost condition might occur if removal starts between 30 and 35 inches of ice thickness. A removal rate of 50,000 ft^3/day for all four turns (corresponding to 0.216 in/day) starting at 31 inches of ice thickness was chosen as the design removal rate for the concept screening and design study. This would mean 66 days of removal in a severe winter and is a removal rate 23 percent of the biweekly design removal rate previously selected.

For 50,000 ft^3/day starting at 31" of ice thickness, no ships would get stuck in the turns in any winter including the most severe. The worst delay experienced in the severe winter would be 9.56 hours over the open water transit time.

A similar set of curves for the St. Lawrence River is presented in Figures 6.6 to 6.9. Figure 6.6 shows a representative curve of average ship delay hours versus removal rate for the ice thickness when there is enough ice to remove and the five winters previously described. Note that the point at which ships start to get stuck in the colder winter occurs at a higher removal rate than the severe winter. This happens because in the particular winters selected there is a two-week period in the colder winter that is more severe than any two week period in the severe winter, even though the total cumulative freezing degree-days is less (the basis for selecting the severity of the winter). Consequently, the colder winters were plotted together on Figure 6.7 and curves of the days of delay over 9 hours are also presented.

Unlike the St. Marys River, it is possible on the St. Lawrence River to experience significant delays without becoming stuck. This is due to the longer length of the river and the fact that the turns are wide enough that the ships don't get stuck any quicker in turns than the straightaways, in general. In this river, the criterion of holding vessels to a maximum 9 hour delay has been chosen (Section 5.). A 9 hour delay is comparable to the delay on the St. Marys River at the point where ships just avoid getting stuck and represents a reasonable compromise--not letting transit times become too different between summer and winter.

Figure 6.1
St. Mary's River
730' Ship 8000 SHP
Removal Starts
when Ice Thickness = 46"



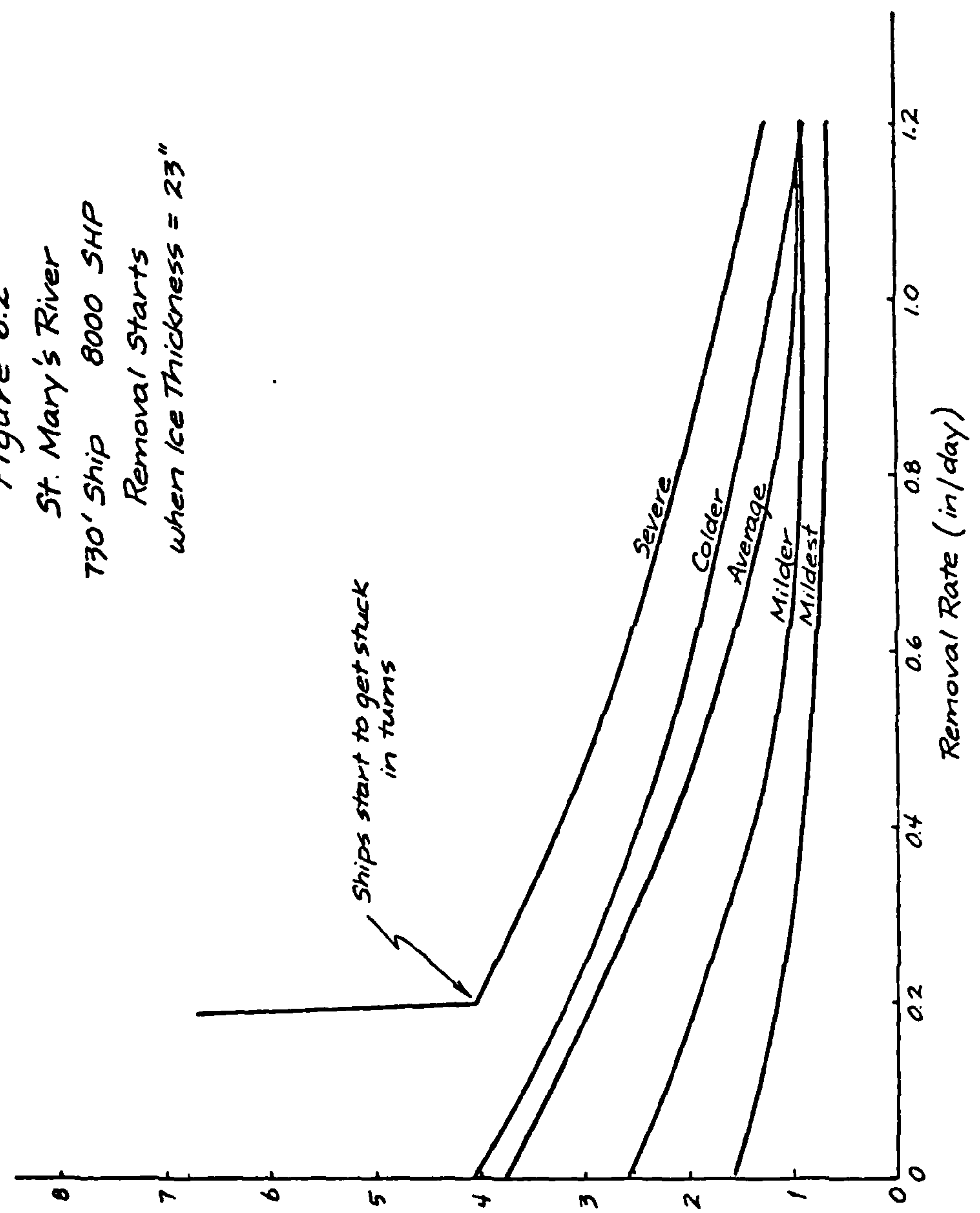


Figure 6.2
St. Mary's River
730' Ship 8000 SHP
Removal Starts
when Ice Thickness = 23"

Figure 6.3
St. Mary's River
730' Ship 8000 SHP
Removal Starts
when There is Ice to
Remove

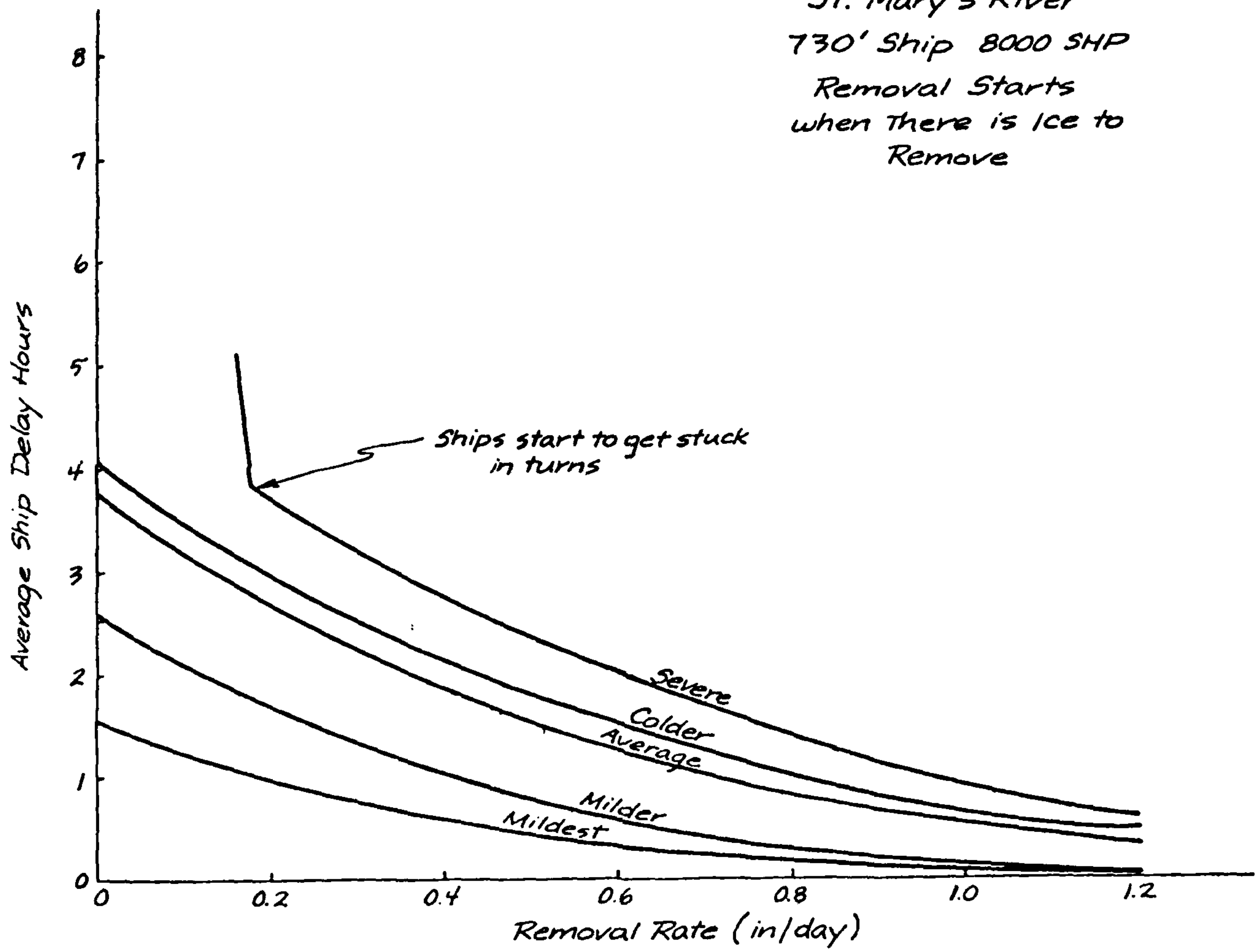


Figure 6.4
Average Ship Delay Hours
for Severe Winters
on the St. Mary's River

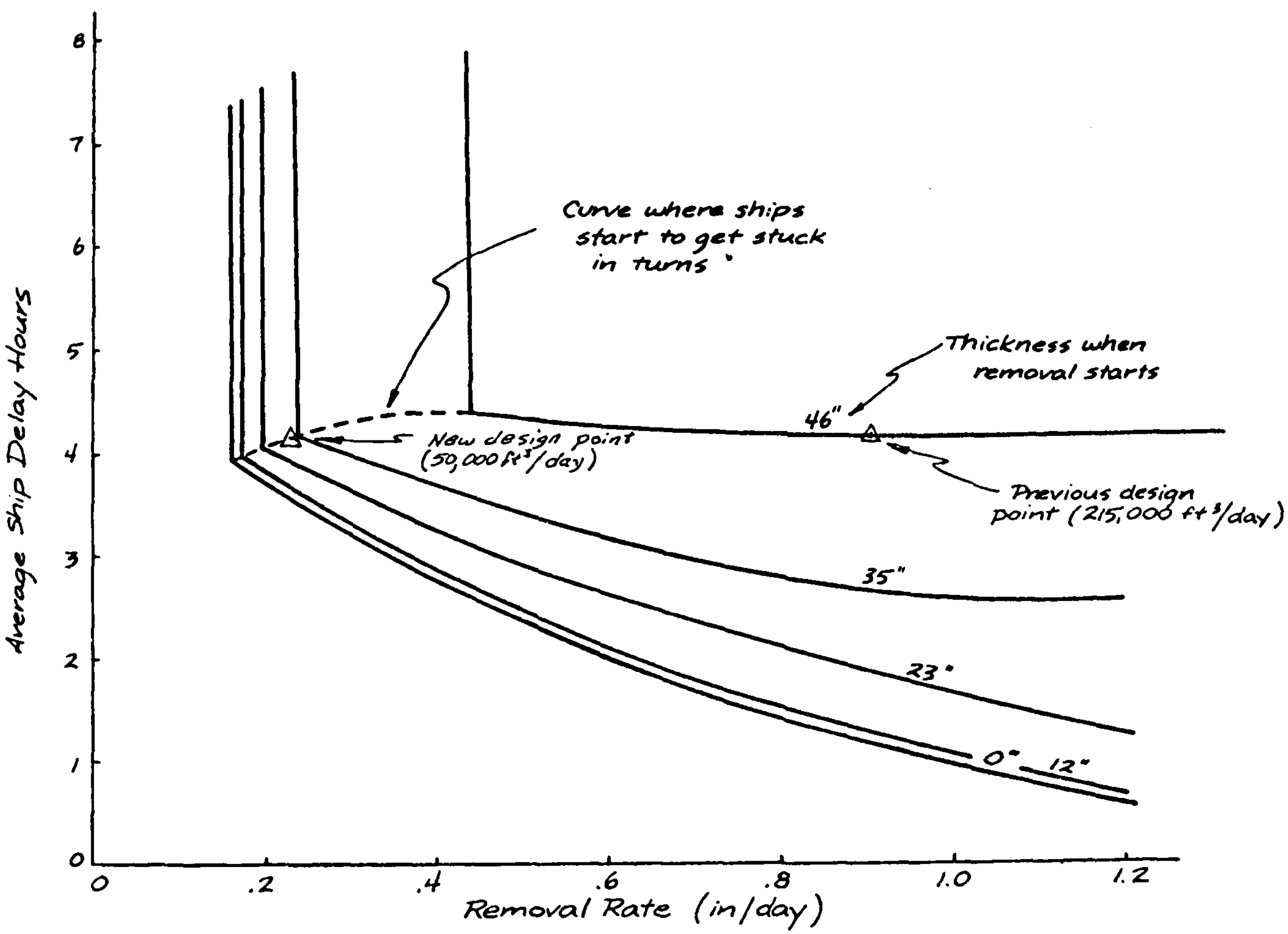


Figure 6.5

Removal Rate at the Inception of Maintaining Traffic in the Turns During a Severe Winter versus Ice Thickness when Removal Starts with Corresponding Cumulative Delay Days, Removal Days, and Total Amounts of Ice Removed

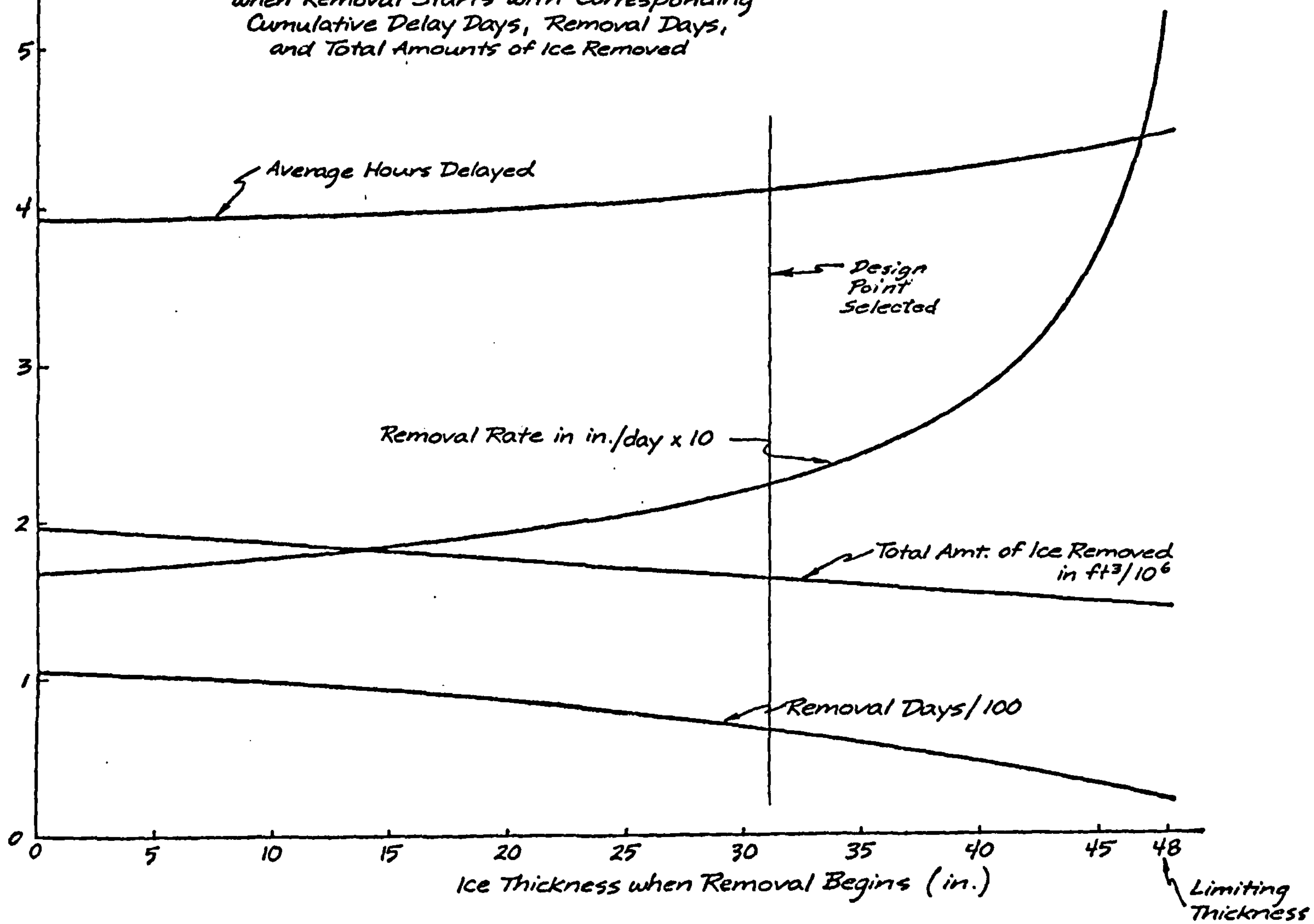


Figure 6.6

St. Lawrence Seaway

(Removal starts as soon as there is ice to remove)

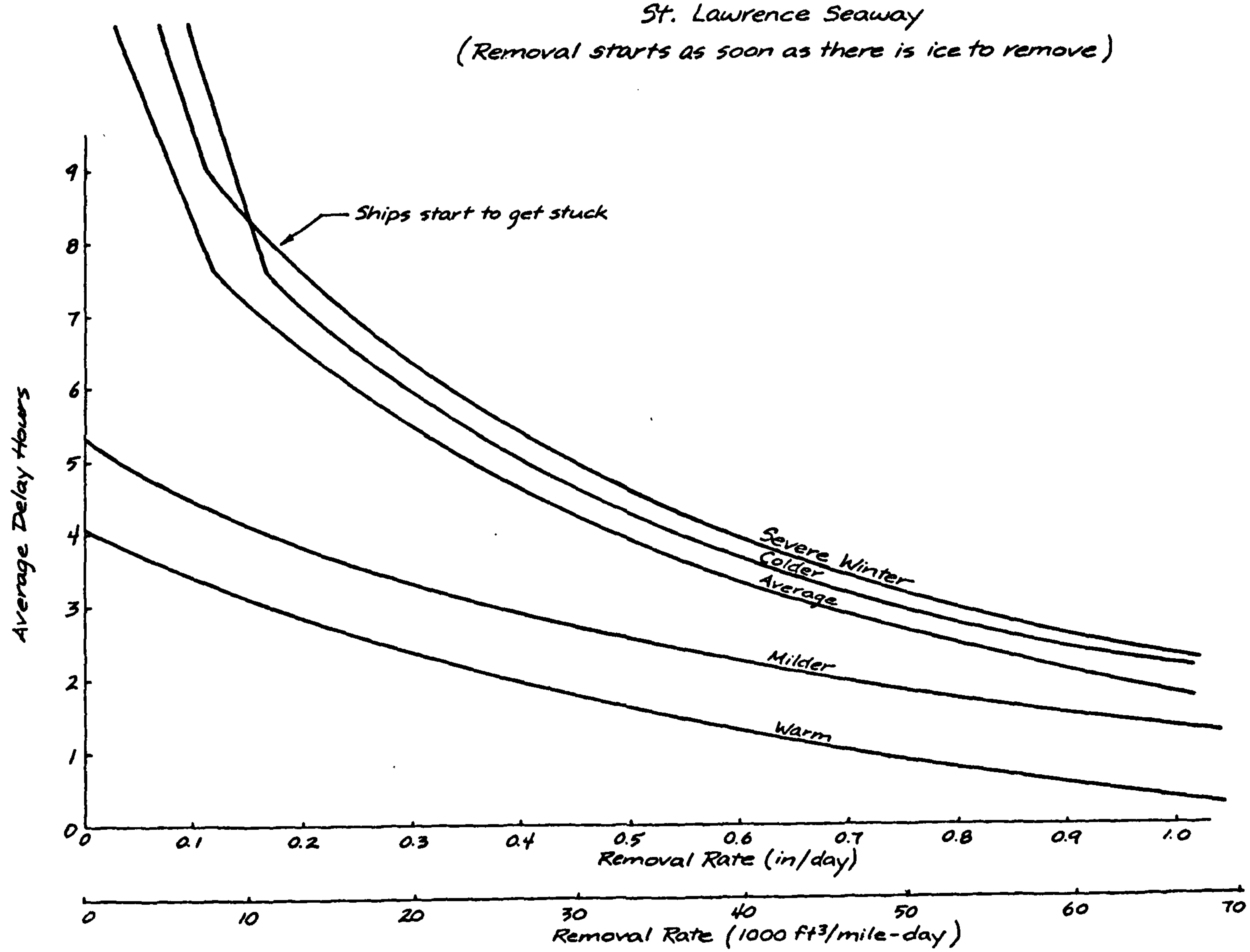


Figure 6.7

St. Lawrence Seaway

Variation in When Ice Removal Starts

Colder Winter

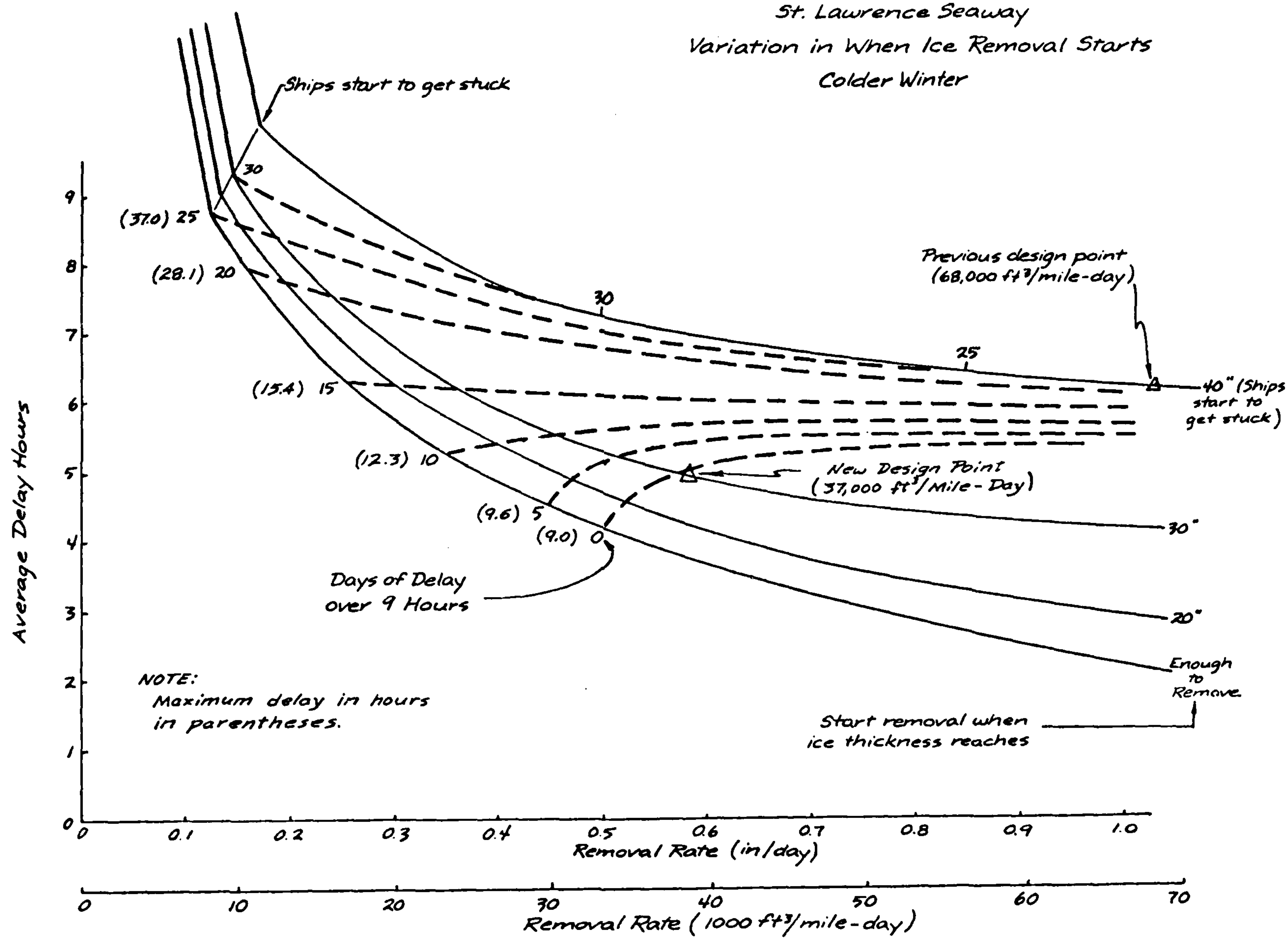
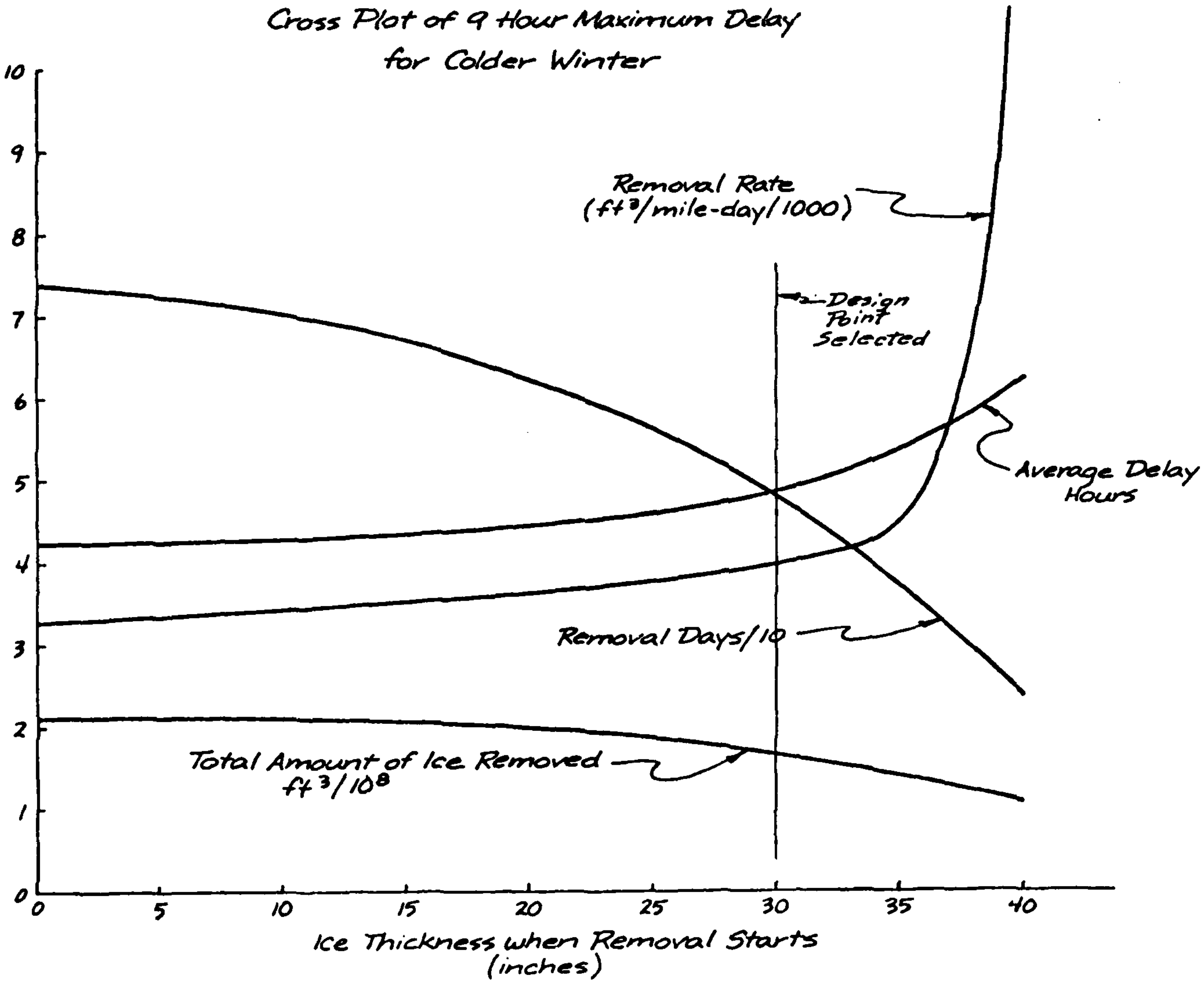


Figure 6.8
St. Lawrence Seaway
Cross Plot of 9 Hour Maximum Delay
for Colder Winter



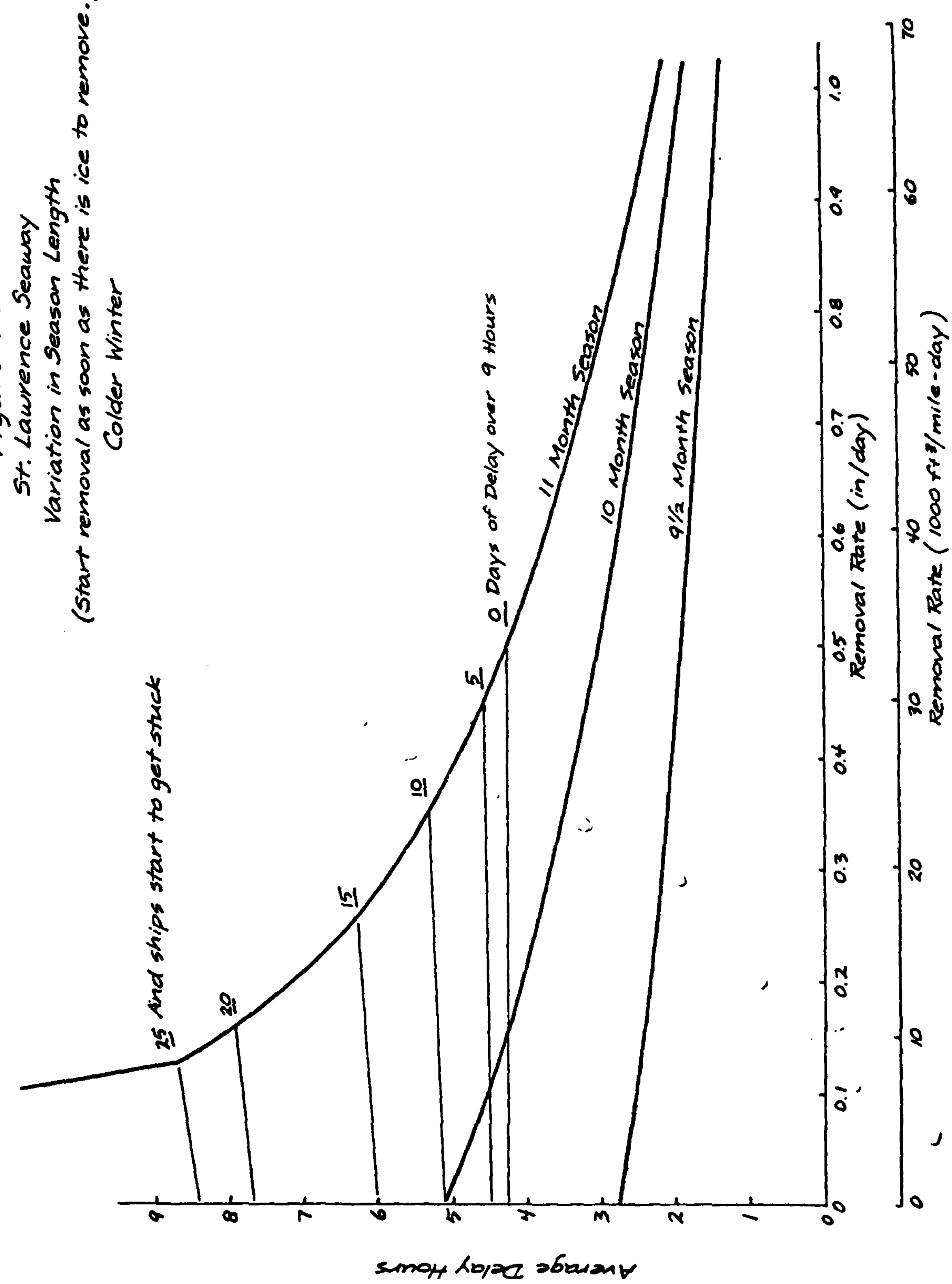


Figure 6.9
St. Lawrence Seaway
Variation in Season Length
(Start removal as soon as there is ice to remove.)
Colder Winter

A crossplot of the points along the dotted curve marked zero days delay over 9 hours on Figure 6.7 is presented in Figure 6.8. Trends in the variables presented are the same as for the St. Marys River. A minimum cost alternative appears to be in the 30 to 35 inch range of thickness when removal starts. For the following design studies, a removal rate of 37,000 ft^3/mile-day was chosen starting at an ice thickness of 30 inches (0.56 in/day). This represents 54 percent of the design removal rate determined by the bi-weekly study and 48 days of removal. No ships would get stuck or have a delay greater than 9 hours even in the most severe winter with this removal strategy.

An additional curve (Figure 6.9) is presented for the St. Lawrence River. This figure shows the effect of a shorter season length. If 10 days where delays exceeded 9 hours in a severe winter with a 10 month season is acceptable (maximum delay 9.6 hours), no removal is necessary for either a 9-1/2 month or 10 month season.

7. DEVELOPMENT OF SYSTEM PERFORMANCE REQUIREMENTS

The U.S. Coast Guard, in requesting this study in the RFP, specified functional areas of importance in considering channel clearing systems. This study has developed system performance requirements in each of those functional areas. The functions identified by the U.S. Coast Guard which the systems must execute are listed in the first column of Table 7.1. The functional performance requirements for ice clogged channel clearing systems on the St. Marys River and the St. Lawrence River are those listed in the second and third columns of Table 7.1. Any system which fails to fulfill all of these requirements will be evaluated as not being feasible and will not be considered further in this project.

The preliminary studies of Section 5 provided information to guide the U.S. Coast Guard in the selection of performance criteria for channel clearing; that is, the specification of the maximum delay any ship can experience on each river. Ice removal on the St. Marys River should not allow ships to get stuck in the turns in any winter. Ice removal on the St. Lawrence River should limit delays to a maximum of 9 hours in any winter. The removal rate study of Section 6 determined the volumetric performance requirements of Table 7.1 based on the above criteria.

It is important to note that several of the requirements differ significantly between the two rivers. The removal rate requirement is much larger on the St. Lawrence River and extends over 87 miles, as opposed to the four specific locations on the St. Marys River. Similarly, the storage requirements are different in terms of quantity and location between the two rivers. Due to the nature of the differences between the recovery and storage requirements, the logistics requirements for the two rivers are also significantly different.

TABLE 7.1 SYSTEM PERFORMANCE REQUIREMENTS

FUNCTION	ST. MARYS RIVER	INTERNATIONAL SECTION ST. LAWRENCE RIVER
DETECTION	The system must be able to establish that vessels are taking excessive amounts of time to negotiate individual turns (>1 hours) and be able to identify specific problem areas.	The system must be able to establish that ice clogged channel vessel delays for the entire International Section are approaching the maximum acceptable delay (9 hours).
ICEBREAKING	The system must be able to break level and refrozen brash ice up to 1.5 feet thick and be able to reduce ice pieces to a convenient size for system recovery, transfer, storage, and ultimate disposal. The system must be able to maintain a negotiable channel width in the turns of 300 feet. The design ice mechanical properties are: $\sigma_f = 103$ psi $\sigma_c = 537$ psi $E = 1.23 \times 10^6$ psi	The system must be able to break level and refrozen brash ice up to 1.5 feet thick and be able to reduce ice pieces to a convenient size for system recovery, transfer, storage, and ultimate disposal. The system must be able to maintain a channel width in the straightaways of 150 feet and a negotiable channel width of 300 feet in Carleton Island Turn. The design ice mechanical properties are: $\sigma_f = 103$ psi $\sigma_c = 537$ psi $E = 1.23 \times 10^6$ psi
RECOVERY	The system must be able to remove unconsolidated and refrozen brash and level ice starting from the outside radius of the turn at the following average daily rates: JOHNSONS POINT TURN: 11.5×10^3 ft^3/day MIRRE POINT TURN: 9.5×10^3 ft^3/day STRIBLINGS POINT TURN: 14.7×10^3 ft^3/day WINTER POINT TURN: 14.2×10^3 ft^3/day	The system must be able to remove unconsolidated and refrozen brash and level ice at the average daily rate of 37,000 ft^3/mile-day for the 87 miles of channel likely to become ice clogged.
TRANSFER	The system must be able to move the ice at the rate at which it is recovered to a storage area without interfering with commercial vessel traffic.	The system must be able to move the ice at the rate at which it is recovered to a storage area without interfering with commercial vessel traffic.
STORAGE	The system must be able to store up to 90 days worth of removed ice in such a way as to not disrupt commercial vessel traffic, the hydraulic regime of the river, or the river or riverbank environment. The total volumes to be stored are: JOHNSONS POINT TURN: 7.59×10^5 ft^3 MIRRE POINT TURN: 6.27×10^5 ft^3 STRIBLINGS POINT TURN: 9.70×10^5 ft^3 WINTER POINT TURN: 9.37×10^5 ft^3	The system must be able to store up to 60 days worth of removed ice in such a way as to not disrupt commercial vessel traffice, the hydraulic regime of the river, or the river or riverbank environment. The total volume to be stored is 1.78×10^6 ft^3/mile.
ULTIMATE DISPOSAL	The sytem must be able to melt all of the ice in the storage area and return the meltwater to the river without disrupting commercial vessel traffic, the hydraulic regime of the river, or the river or riverbank environment.	The sytem must be able to melt all of the ice in the storage area and return the meltwater to the river without disrupting commerical vessel traffic, the hydraulic regime of the river or the river or riverbank environment.
LOGISTICS	The system must consist of only such equipment that can be easily deployed and operated in cold weather and wet conditions. The system should operate in conjunction with existing facilities and require minimal manning with no specialized training requirements. The system should be able to maintain the required average daily removal rates by operating on a standard 40 hour work week. The system should be easily and safely stowed between work periods.	The system must consist of only such equipment that can be easily deployed and operated in cold weather and wet conditions. The system should operate in conjunction with existing facilities and require minimal manning with no specialized training requirements. The system should be able to maintain the required average daily removal rates by operating the equipment on a "mission" basis traveling with the flow of commercial traffic for the length of the International Section. While executing its mission the equipment will operate continuously. The system should be easily and safely stowed between work periods.

8. SCREENING OF ICE CLOGGED CHANNEL CLEARING CONCEPTS

8.1 Presentation of Concepts

The channel clearing concepts have been grouped into five disposal categories by the U.S. Coast Guard:

1. Disposal by Slurry
2. Disposal by Displacement Under Ice Cover
3. Disposal by Ejection on Top of Adjacent Ice Cover
4. Disposal by Rafting
5. Disposal by Melting

The acceptability of a channel clearing concept is determined by evaluating whether or not it meets all of the system performance requirements presented in Table 7.1. Twenty-five ice clogged channel clearing concepts have been identified and have been evaluated in Section 8.3. The rationale used in determining the acceptability of each concept is based on the preliminary evaluation of the system performance requirements presented in the next section--Section 8.2, as well as a brief discussion of prevention.

A brief description of each of the proposed concepts is contained in Table 8.1. A more complete description, with a sketch is provided in Appendix H. Of the twenty-five concepts, four concepts employed disposal by slurry, four employed disposal by rafting, three employed disposal by displacement under adjacent ice cover, seven concepts employed disposal by ejection on top of the adjacent ice cover, and seven concepts employed disposal by melting.

TABLE 8.1 ICE CLOGGED CHANNEL CLEARING CONCEPTS

A. DISPOSAL BY SLURRY

CONCEPT NUMBER	CONCEPT DESCRIPTION
A-1	A pusher craft would feed brash ice into a barge mounted ice cutter-slurry pump system. The brash ice would then be pumped via a pipeline to a storage area located in the river, on land, or on top of the ice sheet.
A-2	An ice cutting-slurry pump unit would be attached to the bow of a high powered 730. The brash ice would be pumped on board the ship. After the ship is filled with brash ice, it proceeds to Lake Ontario where the brash ice is pumped over the rear of the ship. By pumping over the stern, the turbulence in the wake is used to mix the brash ice with the already broken channel ice.
A-3	An ice cutting-slurry pump mechanism would be attached to the bow of a 730. The brash ice collected would then be disposed of by pumping it over the side onto the top of the unbroken ice.
A-4	An ice cutter-slurry pump device would be attached to a vessel. The brash ice would be transferred to a barge. Disposal would consist of having a slurry pump on the barge pump the brash ice overboard. The barge would be towed to Lake Ontario.

B. DISPOSAL BY RAFTING

CONCEPT NUMBER	CONCEPT DESCRIPTION
B-1	High powered tug or Archimedean Screw Tractor pushes brash ice into storage area which is located outside of the channel.
B-2	Self-contained conveyor belt unit transfers brash ice in channel to storage area.
B-3	A rectangular flat plate sweeper is mounted to an anchored piling. The plate is slightly wider than the channel. The plate would rotate and clear the brash ice from the channel. After clearing the plate would rotate up to minimum resistance to flow where the process would be repeated.
B-4	A dirigible with scoop would drag brash and deposit it in storage area.

TABLE 8.1 ICE CLOGGED CHANNEL CLEARING CONCEPTS (Continued)

C. DISPOSAL BY DISPLACEMENT UNDER ADJACENT ICE COVER

CONCEPT NUMBER	CONCEPT DESCRIPTION
C-1	Ship mounted (single of double) diverter pushes ice underneath ice cover.
C-2	A slurry pump would be used to shoot ice underneath ice cover.
C-3	Pusher plates are attached to each side of a 730. The plates would extend out from the sides of the ship and push the brash ice under the ice cover.

D. DISPOSAL BY EJECTION ON TOP OF ADJACENT ICE COVER

CONCEPT NUMBER	CONCEPT DESCRIPTION
D-1	A ship mounted conveyor belt, ice cutter-slurry pump, or blower type device would be used to transfer the brash ice from the channel to the top of the adjacent ice cover. The brash ice would be gathered by an ice cutter-slurry pump device and then shot out of a pump so that the brash ice lands on top of the ice. The brash ice would be gathered by a ice cutter-slurry pump (brash ice) device and then thrown onto the top of the ice cover via a blower type device.
D-2	Buckets (large) would be used to pick up the brash ice and drop it on the adjacent ice cover.
D-3	A diverter bow would be mounted to a high powered vessel and divert the ice to the top of the ice cover.
D-4	A catapult-bucket device would pick up the brash ice from the channel and then hurl it onto the adjacent ice cover.
D-5	An ice cutter-slurry pump device would be used to gather the ice. The brash ice would then be compacted into blocks. The blocks would then be pushed over onto the adjacent ice cover.
D-6	A ramp (movable) would be positioned next to the adjacent ice cover. A pusher craft would then push the ice onto the ramp and then to the top of the ice cover.
D-7	A dirigible scoops up brash ice which is then deposited onto the top of the ice cover.

TABLE 8.1 ICE CLOGGED CHANNEL CLEARING CONCEPTS (Continued)

E. DISPOSAL BY MELTING

CONCEPT NUMBER	CONCEPT DESCRIPTION
E-1	Utilize waste heat from factories and power plants to heat water.
E-2	Use hydroelectric power to warm water.
E-3	Use fossil fuel to heat water.
E-4	Construct solar collectors to heat water.
E-5	Ship mounted burners would melt brash as ship proceeds through the channel.
E-6	Windmill driven impeller would circulate water to minimize brash ice growth rate.
E-7	Windmill driven generator would produce electricity which, in turn, would be used to heat the water and melt the brash.

8.2 Preliminary Evaluation of System Performance Requirements

This evaluation was performed in order to obtain a quantitative understanding of the system performance requirements and also to establish a rationale for evaluating each disposal method and its related concept functions. The system performance requirements for each of the five disposal methods are discussed below.

Disposal by Slurry

If a channel clearing concept is to implement disposal by slurry, the slurry transfer rates would be determined by the "Recovery" system performance requirement of Table 7.1. For the St. Lawrence River, the slurry pump would be required to remove ice at an average daily rate of 37,000 cubic ft/mile-day for the 87 miles of channel likely to be clogged. For the four turns in the St. Marys River, the slurry pump must remove ice at average rates from 9,500 to 14,700 cubic feet per day. The slurry transfer rate also depends upon the sweeprate of the vessel; that is, the intake volume rate of brash ice should be equal to the volume flowrate of the slurry transfer system. Table 8.2 presents the slurry transfer requirements for both the St. Lawrence and the St. Marys River. The transfer rates are based on an 8-hour work day (6 hours actually removing ice) for both the St. Marys and the St. Lawrence River. To achieve the very large flowrates for the system operating on the St. Lawrence River, a multi-unit system and 24 hour operating days may be required.

Table 8.3 indicates the storage requirements for the four turns of the St. Marys River for alternatives requiring a storage area. For example, in the Johnson Point Turn, a brash ice pile of 94 ft would require a storage are of 175 ft in diameter. This area would be located outside the channel in shallow water or on land.

For the St. Lawrence River the sweeprate "requirement" is somehwat different than that of the St. Marys River. The brash ice along the St. Lawrence River must be removed in a uniform manner along the 87 miles of channel likely to become ice clogged. Also, the brash ice removal system must travel with the flow of commercial traffic. A centralized storage area becomes more difficult. Several storage areas along the river would be required. However, it appears that the slurry disposal method may be acceptable for use on the St. Marys and St. Lawrence Rivers.

Disposal by Displacement Under/Over Ice

For the concept implementing disposal of the brash ice by displacement under/over the ice, the "STORAGE" system performance requirement must be met. For the St. Lawrence River, the total volume of brash ice to be stored for an entire winter under/over the ice is 1.78×10^6 ft^3/mile. For the four Turns in the St. Marys River, the total volume of brash ice to be stored under/over the the ice cover ranges from 627,000 ft^3 to 970,000 ft^3. Tables 8.4 and 8.5 indicate the total depth/height of brash ice to be stored under/over the ice as determined from the system performance requirements for the St. Lawrence and St.

TABLE 8.2 SLURRY PUMP FLOWRATE REQUIREMENTS FOR BRASH ICE REMOVAL

ST. MARYS RIVER:

	TOTAL VOLUME PER DAY (ft^3)	REQUIRED BRASH ICE REMOVAL RATES* (ft^3/hour)	(CFM)	(GPM)
Johnson Pt.	11.5×10^3	1917	32.0	239
Mirre Pt.	9.5×10^3	1583	26.4	198
Stribling Pt.	14.7×10^3	2450	40.8	306
Winter Pt.	14.2×10^3	2367	39.5	295

ST. LAWRENCE RIVER:

	TOTAL VOLUME PER DAY (ft^3)	NUMBER OF SYSTEMS	REQUIRED BRASH ICE REMOVAL RATES (ft^3/hour)*	(CFM)	(GPM)
37000 ft^3/(mile-day) for 87 miles and 48 days	3.22×10^6	1	536,500	8940	67,000
		2	268,300	4470	33,500
		3	178,800	2980	22,300

* Based on an 8-hour work day (6 hours actually clearing).

TABLE 8.3 HEIGHT AND DIAMETER OF STORAGE AREA BRASH ICE PILE BASED ON AN ANGLE OF REPOSE OF 47°

ST. MARYS RIVER

	TOTAL VOLUME (ft^3)	BRASH ICE PILE HEIGHT (ft)	DIAMETER OF STORAGE AREA (ft)
Johnson Pt.	759,000	94	175
Mirre Pt.	627,000	88	164
Stribling Pt.	970,000	102	190
Winter Pt.	937,000	101	187

Marys River, respectively. Results of Table 8.4 for the St. Lawrence River indicate that if the brash ice is stored in a limited area on both sides of the ship channel under/over the ice, this large pile of brash ice may break the ice cover if stored on top or would largely fill the available water depth at some areas in the St. Lawrence River. Evenly spreading the ice over, say, 50 feet to a depth of 3.4 feet would be necessary.

A similar analysis, presented in Table 8.5 was performed for the four turns in the St. Marys River. It was assumed that the brash ice could be stored on or under the ice cover at the outside of each turn. For example, the radius of the outside of the Winter Pt. Turn was equal to 3,850 ft and it was hypothesized that ice could be stored to a radius of 3,900 ft. The arc length of the turn was calculated to be equal to 3,763 ft. If the brash ice could be stored over a width of 50 ft under the ice (3,850 to 3,900 ft radius), then the brash ice pile depth would be equal to 5.0 feet. This pile depth is less than a fifth of the available channel depth of 27 feet.

Due to the storage of brash ice in the turns of the St. Marys River, increased flow velocities are not anticipated. Table 8.6 indicates the blockage due to brash ice storage for each turn of the St. Marys River. It was assumed that all of the brash ice would be stored in the 28 ft deep channel (27 ft for Winter Pt. Turn). The volume of the turn was estimated from nautical charts.

Storage on top of the ice at the four Turns in the St. Marys River appears not acceptable for the following reasons. There exists the possibility that a portion of the thickened ice sheet could break away from the thinner ice, move into the shipping channel and block shipping. This very thick "runaway" ice piece would then need to be removed or broken up and thus place additional icebreaking requirements on the selected concept. The idea of storing ice behind an ice boom does, however seem practical. The storage pile depth is sufficiently less on the St. Lawrence River that storage on the ice cover seems feasible, however, this would have to be examined carefully before a system such as this could be implemented.

Disposal by Rafting

For concepts implementing disposal by rafting areas outside the shipping channels along the St. Lawrence River would need to be identified as being suitable for the storage of the brash ice. For the St. Lawrence River, these areas should be relatively deep and large. Eleven such areas have been identified and appear to be suitable storage of brash ice. Table 8.7 gives a description of the storage areas; miles to be covered; total volume of brash ice for each storage location; and length, breadth, and depth. It should be noted that two of the eleven areas are on land. The minimum depth quoted is the smallest value quoted on the nautical charts for the area of interest. The length of the storage areas range from 0.22 to 2.6 miles

TABLE 8.4 BRASH ICE PILE HEIGHTS FOR THE ST. LAWRENCE RIVER

ST. LAWRENCE RIVER	TOTAL VOLUME PER MILE FOR 48 DAYS	TOTAL VOLUME/FOOT (ft^3/ft)
37000 ft^3/(mile-day) for 87 miles and 48 days	1.78×10^6 ft^3	336

STORAGE OF ICE ON BOTH SIDES OF CHANNEL

Assuming a Pile

$$\frac{2H_B}{W_B} = \tan 47°$$

$$\text{Area} = \frac{H_B W_B}{2}$$

$$= \frac{\tan 47° \, W_B^2}{4}$$

Vol/ft = 2 Area

W_B = 25 ft H_B = 13.4 ft

Assuming uniformly spread over 50 ft W_B = 50 ft H_B = 3.4 ft

STORAGE OF ICE UNDER BOTH SIDES OF CHANNEL

$$\frac{2D_B}{W_B} = \tan 33°$$

$$\text{Area} = \frac{D_B W_B}{2}$$

$$= \frac{\tan 33° \, W_B^2}{4}$$

Vol/ft = 2 Area

W_B = 32.2 ft

D_B = 10.5 ft

TABLE 8.5 BRASH ICE PILE HEIGHTS FOR THE FOUR TURNS IN THE ST. MARYS RIVER

TURN	TOTAL VOLUME OF BRASH ICE TO BE STORED	TURN ARC α(deg)	TURNING RADIUS (ft)	STORAGE AREA* $(ft)^2$	HEIGHT OR DEPTH OF BRASH ICE PILE** (ft)
Stribling Pt.	9.70×10^5	65	3140	180,000	5.3
Mirre Pt.	6.27×10^5	42-1/2	2315	86,800	7.2
Johnson Pt.	7.59×10^5	62-3/4	1785	99,100	7.7
Winter Pt.	9.37×10^5	56	3850	189,000	5.0

* Storage area assumes that brash ice can be stored under or over the ice for a distance of 50 ft from the outside edge of the turn; that is, the storage area is equal to $\pi\alpha/360\ ((R_{Turn} + 50)^2 - R^2_{Turn})$.

** Uniform height across the pile.

TABLE 8.6 CHANNEL BLOCKAGE DUE TO BRASH ICE STORAGE FOR THE FOUR TURNS OF THE ST. MARYS RIVER

TURN	AVAILABLE VOLUME OF THE CHANNEL (ft^3)	VOLUME OF BRASH ICE TO BE STORED (ft^3)	BRASH ICE BLOCKAGE (%)
Stribling Pt.	78.26×10^6	9.70×10^5	1.2
Mirre Pt.	34.72×10^6	6.27×10^5	1.8
Johnson Pt.	44.1×10^6	7.59×10^5	1.7
Winter Pt.	68.85×10^6	9.37×10^5	1.4

$$* \text{ Blockage} = \frac{\text{Brash Ice Volume}}{\text{Available Channel Volume}} \times 100$$

TABLE 8.7 POTENTIAL BRASH ICE STORAGE AREAS IN ST. LAWRENCE RIVER

NO.	AREA	MILES OF COVERAGE	TOTAL VOLUME OF BRASH ICE* (ft^3)	LENGTH OF STORAGE AREA (ft)	MIN DEPTH (ft)	WIDTH (ft)
1	Outside Channel - Carleton Island - Sand Bay Area	12.5	22.2×10^6	4600	69	70
2	Outside Channel - Grindstone Island Area	10	17.8×10^6	2300	44	175
3	Outside Channel - Grenadier Island	8.5	15.1×10^6	2300	40	164
4	Outside Channel - Oak Island	8	14.2×10^6	2870	61	81
5	Outside Channel - Brockville - Ogdensburg	14	24.9×10^6	2.6 x 5280	53	34
6	Outside Channel - Upstream of Iroquois Control Dam	4	7.1×10^6	3450	51	40
7	On Land - Odgen Island	5.5	9.8×10^6	1150	89**	178**
8	Outside Channel - Vicinity of Doral Shoals	3.5	6.2×10^6	1150	34	159
9	Outside Channel - Wilson Hill Island Anchorage Area	6	10.7×10^6	2300	47	99
10	Ouside Channel - Deep Areas of Lake St. Lawrence	9	16.0×10^6	3450	41	113
11	On Land - U.S. Side Near Cornwall Island	6	10.7×10^6	1150	93**	185**
	TOTAL	87	154.5×10^6			

* For 48 days of Storage

** [illegible] width of land based brash ice pile based on angle of repose of 47°

Disposal by Melting

The energy requirements are quantified below for a "disposal by melting" concept. The amount of energy required to melt brash ice depends on the volume of brash ice. For the St. Lawrence River the amount of brash ice required to be melted is 1.55×10^8 ft^3. The latent heat of fusion is approximately 8242 BTU/ft^3. Therefore the heat required to melt the required volume of brash ice is 1.27×10^{12} BTU's. Over a 48 day period, this energy requirement translates into a 324 megawatt power requirement. This power level is equivalent to one-sixth the power generation capability of the Moses-Saunders Power Dam (1950 megawatts) which is located on the St. Lawrence River. It is highly unlikely that power of this magnitude could be diverted from the power grid to melt ice.

For the St. Marys River, the volume of brash ice required to be removed is 3.3×10^6 cubic feet and would require 27.2×10^9 BTU's to melt the ice This energy is equivalent to a 5.0 megawatt power requirement. In the vicinity of the St. Marys River there are two hydroelectric power plants, the Sault St. Marie Power Plant produces 41.3 megawatts and the St. Marys Falls Plant produces 18.4 megawatts of power. The 21.6 megawatt required to melt brash ice represents 8.4 percent of the combined power generated by these two power plants. Again it is highly unlikely that power of this magnitude could be diverted from these two plants to melt ice.

If fuel were burned to generate heat to melt the ice, approximately 9.5 and 0.2 million gallons would be required to melt the brash ice in the St. Lawrence River and St. Marys River, respectively.

Other potential sources of energy to melt ice are the wind and sun. Currently available wind mills generate power on the order of 10,000 watts or 10 KW. For the St. Lawrence River, a minimum of 32,400 windmills of 10 KW capacity would be required to melt the required volume of brash ice. For the St. Marys River, approximately 500 windmills of 10 KW capacity would be required to melt the necessary ice. Although the number of windmills required appears large for both rivers, the energy is free and renewable. Because of these two beneficial factors, the concept of windmills to heat the water was considered acceptable.

Solar energy is another free and renewable form of energy. For the St. Lawrence River and St. Marys River areas, the normal daily value of total hemispheric solar radiation on a horizontal surface is approximately 415 BTU/(ft^2-day). This value represents the average for the months of December, January, and February. To generate 324 megawatts of power in the St. Lawrence River area using solar collectors, a surface of approximately 2.29 square miles would be required. For the St. Marys River which requires 5.0 megawatts of power to melt the brash ice, a solar collector area of 0.036 square miles would be required.

Prevention

The possibility of preventing ice from forming on the river was also considered. The average cross-sectional area of the channel at Stribling Point Turn was estimated to be 14,300 ft^2 and an average river velocity of 2 fps was assumed. This is equivalent to 1.79×10^6 lbs/sec of river flow or 1.29×10^{10} BTU/hr would be required to raise that flowrate 2°F. The electrical power required to produce that amount of energy is 70 megawatts, more power than required to melt the accumulated ice as determined above. Heat would be dissipated rapidly at the water surface such that the 2°F temperature rise would not be maintained very far downstream.

If a 1000 megawatt generating plant were located near the turns on the St. Marys River and waste water was injected at the proper points above the turns, the waste heat would probably be sufficient to keep the turns and a portion of the river clear of ice. Locating a large generating plant on either river cannot, of course, be based solely on channel clearing. Social, economic, and environmental questions may likely preclude this alternative. Anyway, the cost of channel clearing options does not appear to be so severe that alternatives such as this have to be considered.

8.3 Screening of Various Ice Clogged Channel Clearing Concepts

Based on the results of the preliminary evaluation of the system performance requirements, the twenty-five ice clogged channel clearing concepts were screened. Appendix H contains the concept screening results for each of the twenty-five proposed concepts. A sketch of each concept is also contained in Appendix H.

Again, it should be mentioned that the acceptance or rejection of a concept was determined by whether or not it met "all" of the system performance requirements. Each concept was evaluated using the method described in Section 7. The system performance requirements are presented in Table 7.1.

Six concepts were deemed acceptable for the St. Lawrence River and seven concepts were considered acceptable for the St. Marys River. The accepted concepts are presented in Table 8.8 and 8.9 in order of most promising concept; that is, the first concept is the most promising concept.

The most common reasons for rejecting a concept are given below.

- The system is not continuous and does not move with the flow of commercial traffic. This reason applied to systems on the St. Lawrence River. If a concept was thought to interfere with the flow of commercial traffic or the ice removal and storage operations were not continuous, the concept was rejected.

- Storage may break the level ice sheet. A large volume of ice stored on the ice cover could cause the level ice to break off and become a hazard to navigation.

- Special equipment and training is required. If new equipment and training were deemed necessary for the concept, the concept was rejected. For example, the dirigible concept would require a dirigible and specially trained personnel to man and operate the craft.

- Storage method is not feasible. This reason applied to the disposal method of storage under the ice. Brash ice storage requirements indicated that brash ice would need to be distributed under or over the ice for at least a length of 50 feet in a uniform manner. This method was rejected because maintaining control of brash ice movement once under the ice cover is not possible; that is, the brash ice can move anywhere once under the ice cover.

- Energy requirements are excessive and probably not available. Due to the large amount of brash ice required to be melted, melting concepts would require a tremendous amount of energy. For the St. Lawrence River approximately 1.27 x 10^{12} BTUs are required. For the St. Marys River approximately 27.2 x 10^{9} BTUs are required.

TABLE 8.8 MOST PROMISING ICE CLOGGED CHANNEL CLEARING CONCEPTS FOR THE ST. LAWRENCE RIVER

D-1	A ship-mounted conveyor belt, ice cutter slurry pump, or blower type device would be used to transfer the brash ice from the channel to the top of the adjacent ice cover.
A-3	An ice cutting slurry pump mechanism would be attached to the bow of a 730. The brash ice collected would then be disposed of by pumping it over the side onto the top of the unbroken ice.
A-4	An ice cutter slurry pump device would be attached to a vessel. The brash ice would be transferred to a barge. The barge would be towed to Lake Ontario where disposal would consist of having the brash ice pumped overboard.
A-2	An ice cutting slurry pump unit would be attached to the bow of a high powered 730. The brash ice would be pumped on board the ship. After the ship is filled with brash ice, it proceeds to Lake Ontario where the brash ice is pumped over the rear of the ship. By pumping over the stern, the turbulence in the wake is used to mix the brash ice with the already broken channel ice.
E-4	A solar collector unit would be used to heat water and melt brash ice.
E-7	A windmill system would produce electricity which, in turn, would be used to heat the water and melt the brash.

TABLE 8.9 MOST PROMISING ICE CLOGGED CHANNEL CLEARING CONCEPTS FOR THE ST. MARYS RIVER

A-1	A pusher craft would feed brash ice into a barge-mounted ice cutter slurry pump system. The brash ice would then be pumped via a pipeline to a storage area located in the river, on land.
B-1	High powered tug or Archimedean Screw Tractor pushes brash ice into storage area which is located outside of the channel.
B-2	A self-contained conveyor belt unit transfers brash ice in the channel to a storage area.
A-4	An ice cutter slurry pump device would be attached to a vessel. The brash ice would be transferred to a barge. The barge would be towed to Lake Huron where disposal would consist of having the brash ice pumped overboard.
A-2	An ice cutting slurry pump unit would be attached to the bow of a high powered 730. The brash ice would be pumped on board the ship. After the ship is filled with brash ice, it proceeds to Lake Huron where the brash ice is pumped over the rear of the ship. By pumping over the stern, the turbulence in the wake is used to mix the brash ice with the already broken channel ice.
E-4	A solar collector unit would be used to heat water and melt brash ice.
E-7	A windmill system would produce electricity which, in turn, would be used to heat the water and melt the brash.

Based on the results of the concept screening, the three most promising concepts for the St. Lawrence River and the three most promising concepts for the St. Marys River have been identifed and are described below.

ST. LAWRENCE RIVER:

D-1 A ship-mounted conveyor belt, ice cutter slurry pump, or blower type device would be used to transfer the brash ice from the channel to the top of the adjacent ice cover.

A-3 An ice cutting slurry pump mechanism would be attached to the bow of a 730. The brash ice collected would then be disposed of by pumping it over the side onto the top of the unbroken ice.

A-4 An ice cutter slurry pump device would be attached to a vessel. The brash ice would be transferred to a barge. The barge would be towed to Lake Ontario where disposal would consist of having the brash ice pumped overboard.

ST. MARYS RIVER

A-1 A pusher craft would feed brash ice into a barge-mounted ice collection/cutter/transmission system. The brash ice would then be transferred via a pipeline or conveyor to a storage area located in the river or on land.

B-1 High powered tug or Archimedean Screw Tractor pushes brash ice into storage area which is located out of the channel.

B-2 A self-contained conveyor belt unit transfers brash ice in the channel to a storage area.

9. ALTERNATIVE DESIGNS

The most desirable concepts from the concept screening were presented in the conclusion of the previous section. The U.S. Coast Guard determined that alternatives A-1 and B-1 for the St. Marys River and D-1 for the St. Lawrence River should be developed as conceptual designs. Several variations in the equipment chosen within each concept result in 7 alternative designs. These are as follows:

ST. MARYS RIVER

1. AST's* haul to a barge which crushes and blows the ice to a storage area.
2. 140' WTGB hauls to a barge which crushes and blows the ice to a storage area.
3. AST's haul to a hopper on a conveyor that transports the ice to a storage area.
4. 140' WTGB hauls to a hopper on a conveyor that transports the ice to a storage area.
5. AST's haul to a boom on the outside of a turn.

ST. LAWRENCE RIVER

6. An ice collection barge that conveys ice to the adjacent ice cover and is pushed along the river.
7. Three smaller systems but similar to alternative 6 are pushed along the river.

The objective of this section is conceptual design alternatives of sufficient detail to permit determination of cost estimates. Acquisition costs as well as operating scenarios are presented for the various designs. The development of operating costs and the final selection among the alternatives will be done by the U.S. Coast Guard.

Both 8 and 24 hour operating days are presented for most of the alternatives on the St. Marys River. Eight hour work days are assumed for those cases where the 140 foot WTGB is involved due to the batch nature of its pushing ice and the volume it can move. The WTGB can easily remove the ice from all four turns in eight hours, but since it pushes a large volume of ice to the barge in a single transit and must feed it to the ice collection conveyors, the conveyor or pipeline to the storage area must have a high transfer rate. This rate is not altered with 24 hour operation.

* Archimedean Screw Tractor - Appendix I contains more information about this vehicle.

Twenty-four hour operation is assumed for the St. Lawrence River. The volume of ice to be removed dictates 24 hour operation for conveyor transfer rates to be held to a reasonable level.

9.1 Designs for the St. Marys River

Components of the systems designed for use on the four turns of the St. Marys River satisfy 3 functions; ice gathering, ice removal from the water, and transport to a storage area. The ice collection craft that perform the first function and that are considered for this study are the Archimedean Screw Tractor (AST) and the U.S. Coast Guard 140' WTGB. These two vehicles represent two different concepts in ice gathering; the WTGB would push ice to a collection point with a plow similar to a bulldozer blade where the AST would scoop the ice out of the water and carry it to the collection point with a self-draining bucket similar to a front-end loader. The AST thus performs the second function of removing the ice from the water as well. The volume of ice that a WTGB can push is so large that a loader type bucket would be impractical.

The volume of brash ice that the WTGB could push and the plow size were determined using the equation for resistance of the WTGB in brash ice with air bubblers off from Reference [27], as shown in Appendix J. The volume is dependent on the thicknesses encountered, the average thickness encountered for the 66 days requiring removal in the severe winter design was calculated. The average thickness and its associated volume as well as other thicknesses and volumes are presented in Table 9.1. The volume associated with the average ice thickness will be used in the operational scenarios.

The AST load carrying capability is about 3 tons at 6 mph extrapolating prototype performance. This corresponds to approximately 5 cubic yards or the equivalent of a caterpillar 966 front-end loader. A prototype AST has been constructed and tested by MITSUI Engineering and Shipbuilding Co., Ltd. Appendix I describes the AST.

Figure 9.1 through 9.4 show the four turns on the St. Marys River in detail. Also shown is the proposed storage areas and proposed collection barge locations. The average round-trip distance for a collection craft was taken as 2200 ft for moving ice to the collection barge location and 400 ft when moving ice to the boom (one alternative uses an ice boom on the outside of the turn). Round-trip times and round-trips per hour are shown in Table 9.2 for the two ice collection craft.

Removal rates for the four turns are shown in Table 9.3 with the required trips per hour for the AST working either an 8 hour day or a 24 hour day and required trips per day for the WTGB. The number of ice collection craft required can be calculated by dividing the round-trips required to meet the removal rate by the round-trips achievable by the ice collection craft.

TABLE 9.1 VOLUMES REMOVED BY A WTGB WITH AN ICE PLOW FOR VARIOUS THICKNESSES

BRASH ICE THICKNESS (ft)	BRASH ICE THICKNESS (ft^3)
1	971
2	3175
3	5542
3-1/2	6427 (avg. thick 41.79")
4	7029

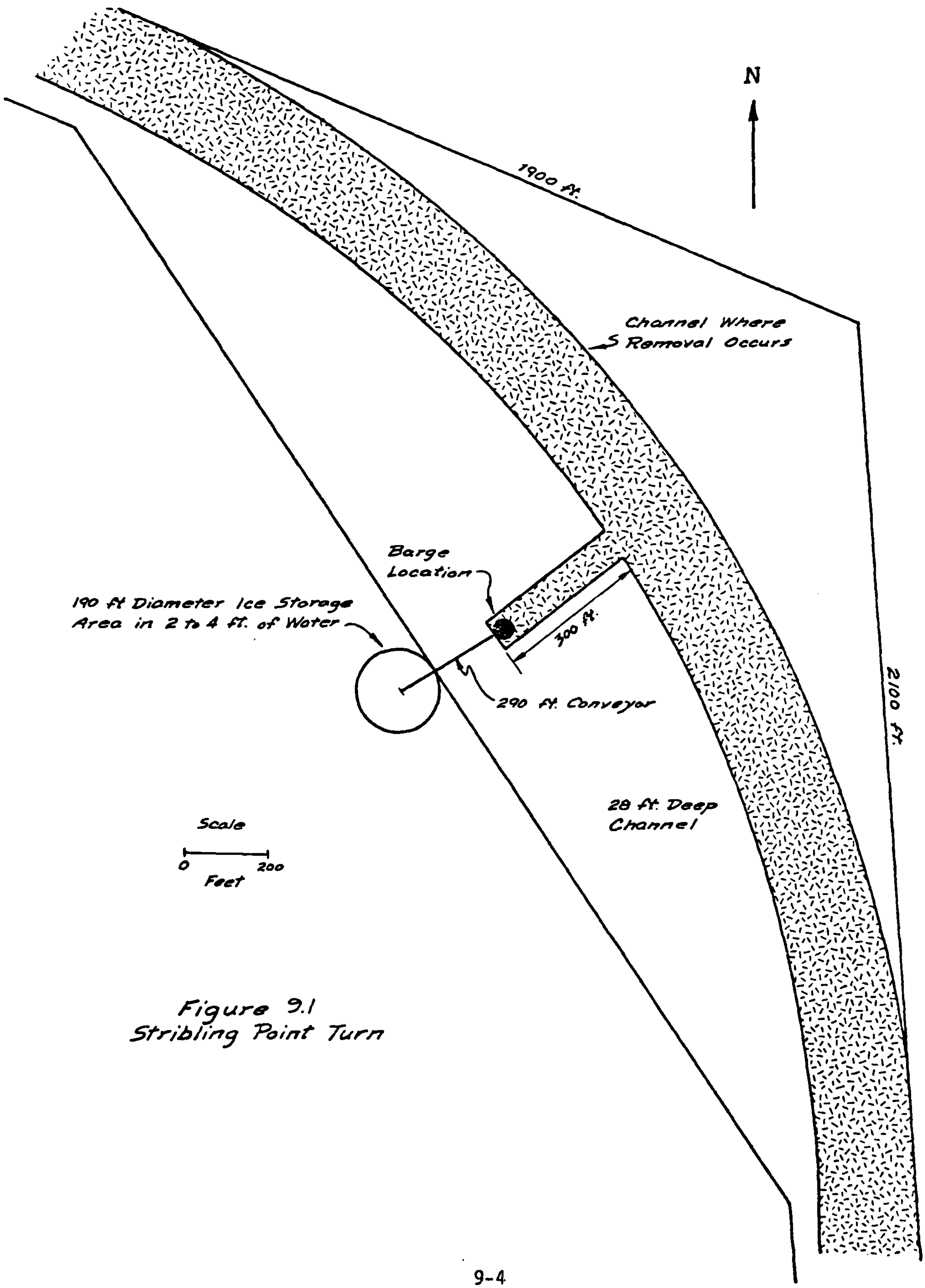


Figure 9.1
Stribling Point Turn

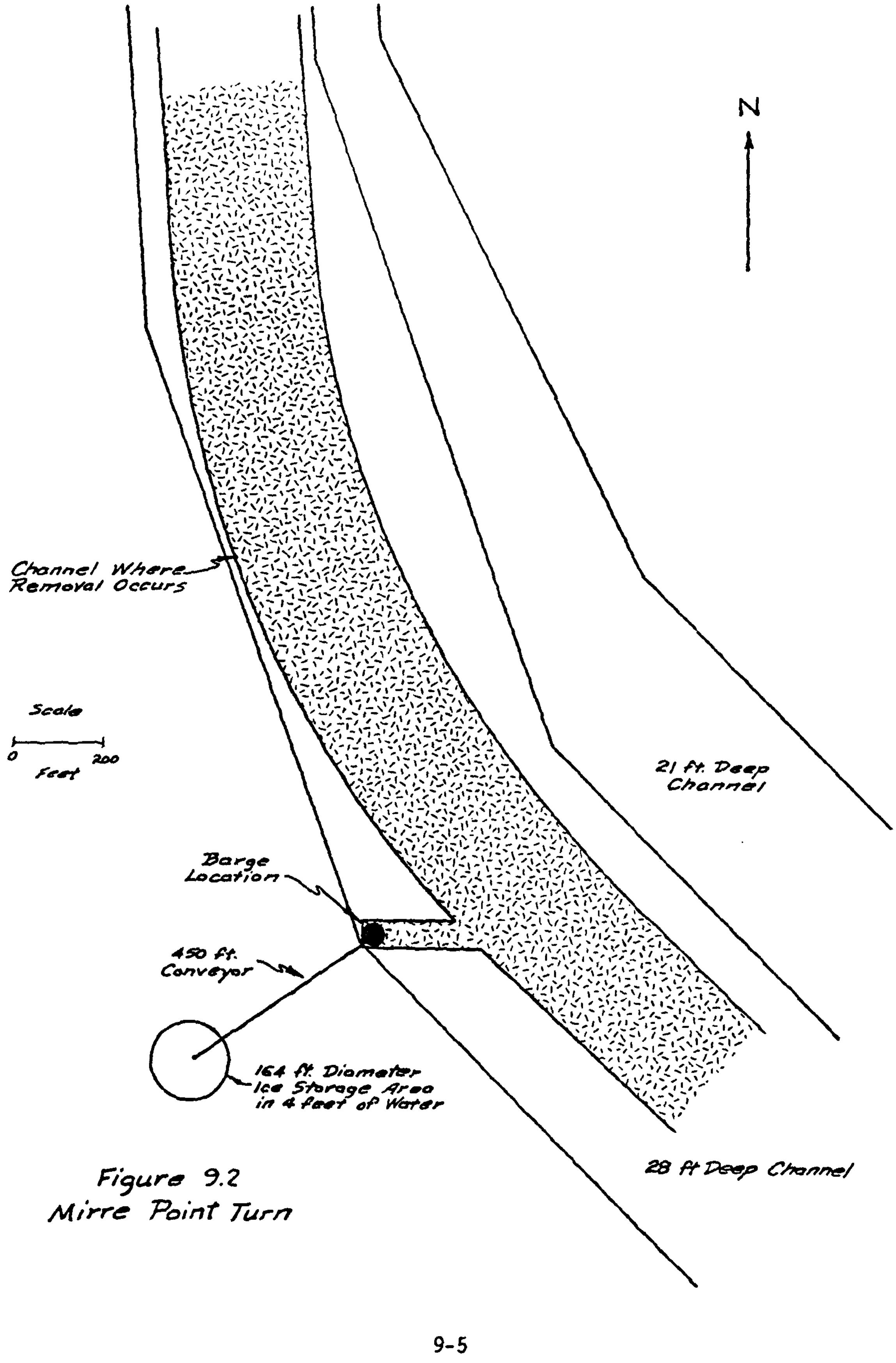


Figure 9.2
Mirre Point Turn

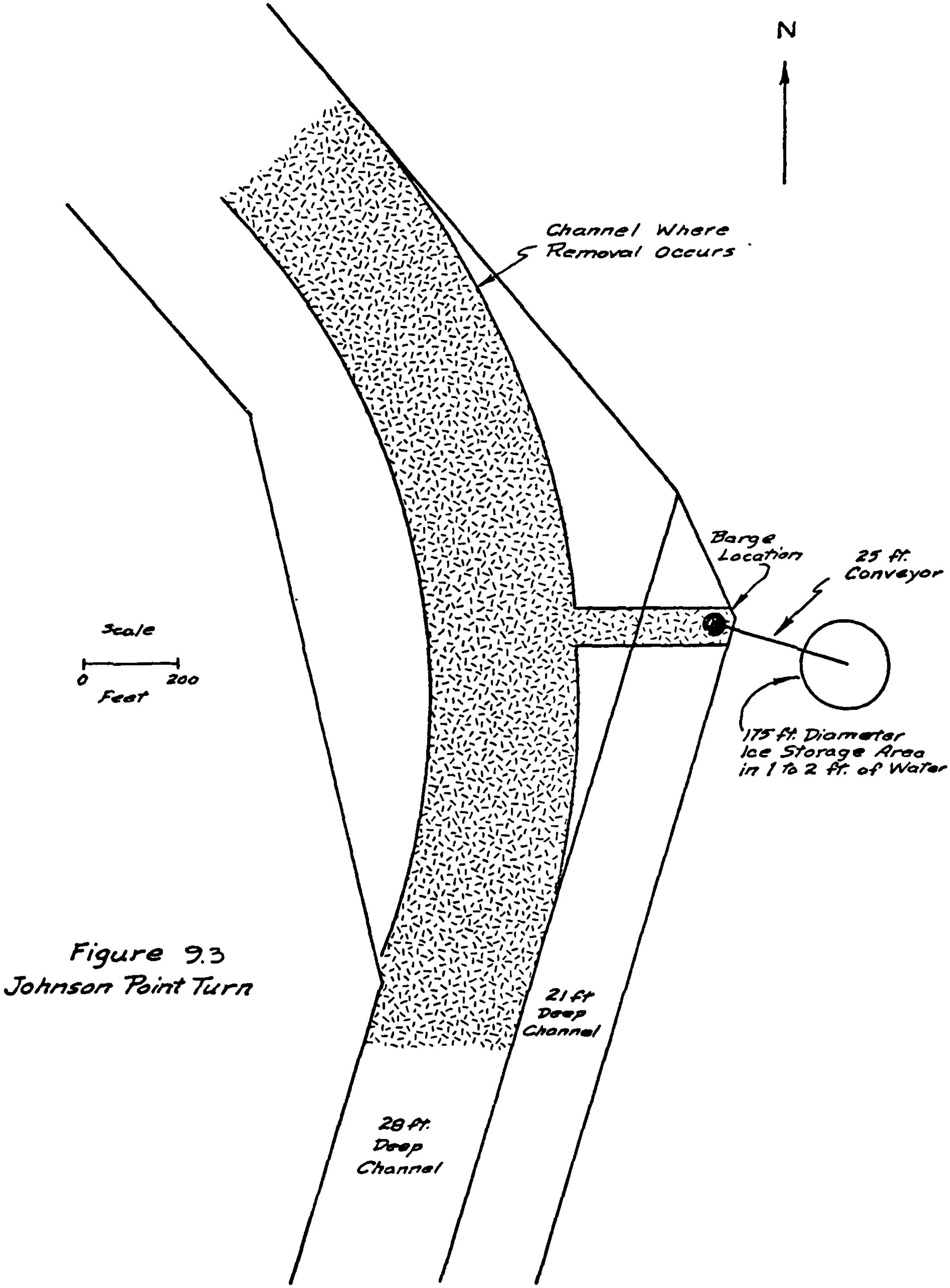


Figure 9.3
Johnson Point Turn

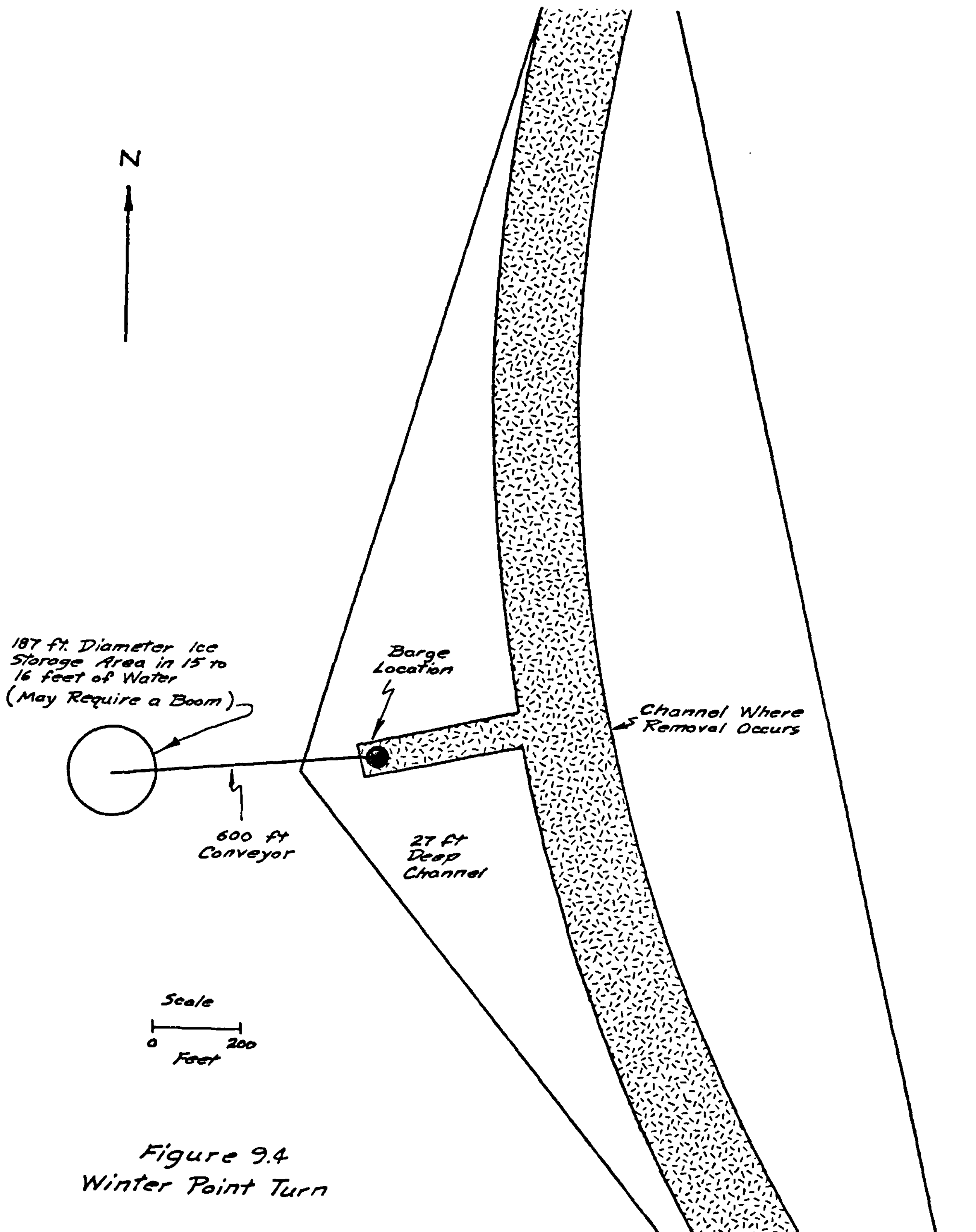


Figure 9.4
Winter Point Turn

TABLE 9.2 ROUND-TRIP TIMES AND ROUND-TRIPS PER HOUR ACHIEVABLE FOR ICE COLLECTION CRAFT

CRAFT	TRANSIT DISTANCE (ft)	TIME (min)	DELAY TIME (min)	TOTAL ROUND TRIP TIME (min)	ROUND TRIPS PER HOUR
AST	2200	4.17	1.83	6	10
	400	0.76	2.24	3	20
WTGB	2200	5.4	24.6 *	30	2

* Long delay is associated with feeding ice to ice collection conveyors.

TABLE 9.3 REQUIRED TRIPS PER HOUR FOR THE FOUR TURNS ON THE ST. MARYS RIVER

TURN	REMOVAL RATE ft^3/day	AST TRIPS/HR REQUIRED 8 HR DAY	AST TRIPS/HR REQUIRED 24 HR DAY	WTGB TRIPS/DAY REQUIRED 8 HR DAY
Johnsons Point	11,500	14.2	4.7	1.79
Striblings Point	14,700	18.2	6.1	2.29
Mirre Point	9,500	11.7	3.9	2.21
Winter Point	14,200	17.5	5.8	1.48
TOTAL		61.6	20.5	7.77

In some cases, one craft could do more than one turn in an operating day. Transit time between the turns was included for these cases. Distances between the centers of successive turns is shown in Table 9.4.

For the second function of removing ice from the water, it is assumed that the WTGB would require ice collection conveyors to bring the ice from the water into a hopper or onto a conveyor. Since the barge doesn't move, the WTGB would be required to push the ice at a steady rate,equal to the transfer rate,into the conveyors. The AST could feed a hopper directly without conveyors.

Two means of transport to a remote storage pile were considered; one using a conventional belt conveyor and one using pneumatic conveying through a pipeline. The pneumatic method is more suitable (presumably cheaper) for small flowrates and the conventional conveyor is more suitable for the larger flows.

A pneumatic conveyor requires an ice crusher, a blower, and rotary valve to inject the ice into the pressurized line, and a power source. A crusher was not included in the conventional conveyor system; ice piece size was assumed less than 3 feet in its largest dimension and weights and costs are figured for a 5 foot wide conveyor. Information gathered for these large conveyors assumes a self-contained unit so no additional power source was included. Equipment for these systems is barge mounted and located slightly removed from the center of each turn. Conveying lengths and locations are shown in Figures 9.1 through 9.4.

Equipment was sized for the removal rate on each turn based on actual hardware. Weight estimates for the barges for each alternative are presented in Tables 9.5 and 9.6. Acquisition costs are presented in Tables 9.7 through 9.10 for each alternative.

One can see that the AST's must be operated 24 hours a day to minimize the number of these relatively expensive craft required. Even with the 24 hour day, Alternatives 1 and 3 are as expensive as Alternatives 4, a WTGB pushing ice to a pneumatic conveyor. At high transfer rates such as alternative 4, the high equipment requirements and costs become apparent. The least acquisition cost solutions, therefore, are alternatives 2 and 5, both roughly the same cost. Alternative 2, a single WTGB feeding an ice collection barge/conventional conveyor system on each turn, and alternative 5, a single AST dumping ice over an ice boom on the outside of each turn, should be carefully analyzed.

TABLE 9.4 DISTANCE BETWEEN SUCCESSIVE TURNS ON THE ST. MARYS RIVER

Striblings Point Turn to Mirre Point Turn	3-1/4 miles
Mirre Point Turn to Johnson Point Turn	1 mile
Johnson Point Turn to Winter Point Turn	3-3/4 miles
TOTAL	8 miles

TABLE 9.5 WEIGHT ESTIMATE FOR CLOGGED CHANNEL CLEARING SYSTEM FOR ST. MARYS RIVER AST'S FEEDING COLLECTION BARGE/ PIPELINE SYSTEM

ALTERNATIVE 1

QUANTITY	COMPONENT	TOTAL WEIGHT
	8 HOUR OPERATING DAY	
1	Ice Crusher (18" x 36")	4 T
1	Blower (about 2500 CFM)	1 T
1	Diesel Engine (250 HP)	2 T
6600 gals	Fuel (66 day endurance)	21 T
1	Fuel Tank	2 T
	Ice Weight (3 AST loads)	11 T
	Subtotal	41 T
	20% Margin	8 T
	Subtotal	49 T
	80 T Barge L.S. Weight	28 T
	TOTAL	77 T
	24 HOUR OPERATING DAY	
1	Ice Crusher (18" x 36")	4 T
1	Blower (about 750 CFM)	1 T
1	Diesel Engine (100 HP)	1 T
7900 gals	Fuel (66 day endurance)	25 T
1	Fuel Tank	3 T
	Ice Weight (2 AST loads)	8 T
	Subtotal	42 T
	20% Margin	8 T
	Subtotal	50 T
	80 T Barge L.S. Weight	28 T
	TOTAL	78 T

TABLE 9.6 WEIGHT ESTIMATE FOR CLOGGED CHANNEL CLEARING SYSTEM FOR ST. MARYS RIVER 140' WTGB FEEDING A COLLECTION BARGE/ PIPELINE OR CONVEYOR SYSTEM

ALTERNATIVE 2 AND 4

QUANTITY	COMPONENT	UNIT WEIGHT	TOTAL WEIGHT
	8 HOUR OPERATING DAY		
1	Ice Crusher (36" x 84")		23 T
4	Blowers (6000 CFM)	1 T	4 T
4	Diesel Engines (450 HP)	3 T	9 T
1	Diesel Engine (150 HP)		1 T
7	Ice Collection Conveyors	2 T	14 T
6300 gals	Fuel (8 days endurance)		20 T
1	Fuel Tank		2 T
	Ice Weight		5 T
	Subtotal		79 T
	20% Margin		16 T
	Subtotal		95 T
	150 T Barge L.S. Weight		54 T
	TOTAL		149 T
	8 HOUR OPERATING DAY		
7	Ice Collection Conveyors	2 T	14 T
	Ice Weight		3 T
	Subtotal		17 T
	20% Margin		3 T
	Subtotal		20 T
	31 T Barge L.S. Weight		11 T
	TOTAL		31 T

TABLE 9.7 COST ESTIMATE FOR CLOGGED CHANNEL CLEARING SYSTEM FOR ST. MARYS RIVER AST'S FEEDING COLLECTION BARGE/ PIPELINE SYSTEM FOR EACH TURN

ALTERNATIVE 1

QUANTITY	COMPONENT	UNIT COST	TOTAL COST
	8 HOUR OPERATING DAY		
4	Ice Crushers (18" x 36")	$ 34 K	$ 136 K
4	Diesel Engines (250 HP)	29 K	116 K
4	Blowers (2000 to 3000 CFM)	8 K	32 K
4	Fuel Tanks (6600 gal)	3 K	12 K
4	Barges (80 T)	46 K	184 K
	Subtotal	$120 K	$ 480 K
	20% Margin	24 K	96 K
	Subtotal	$144 K	$ 576 K
4	Pipelines (3'8" IPS, 1-10" IPS)		114 K
7	Ice Collection Craft (AST's)	700 K	4900 K
	TOTAL		$5590 K
	24 HOUR OPERATING DAY		
4	Ice Crushers (18" x 36")	$ 34 K	$ 136 K
4	Diesel Engines (100 HP)	12 K	48 K
4	Blowers (635 to 900 CFM)	6 K	24 K
4	Fuel Tanks (7900 gal)	4 K	16 K
4	Barges	46 K	184 K
	Subtotal	$102 K	$ 408 K
	20% Margin		82 K
4	Pipelines (3-5" IPS, 1-6" IPS)	90 K	360 K
3	Ice Collection Craft (AST's)	700 K	2100 K
	TOTAL		$2950 K

TABLE 9.8 COST ESTIMATE FOR A CLOGGED CHANNEL CLEARING SYSTEM FOR ST. MARYS RIVER AST'S FEEDING A HOPPER/CONVEYOR SYSTEM ON EACH TURN

ALTERNATIVE 3

QUANTITY	COMPONENT	UNIT COST	TOTAL COST
	8 HOUR OPERATING DAY		
4	Conveyors (5' wide)		$ 736 K
4	Hoppers	$ 5 K	20 K
7	Ice Collection Craft (AST's)	700 K	4900 K
	TOTAL		$5656 K
	24 HOUR OPERATING DAY		
4	Conveyors (5' wide)		$ 736 K
4	Hoppers	$ 5 K	20 K
3	Ice Collection Craft (AST's)	700 K	2100 K
	TOTAL		$2856 K

TABLE 9.9 COST ESTIMATE FOR A CLOGGED CHANNEL CLEARING SYSTEM FOR ST. MARYS RIVER 140' WTGB FEEDING A HOPPER BARGE/ CONVEYOR SYSTEM ON EACH TURN

ALTERNATIVES 2 AND 4

QUANTITY	COMPONENT	UNIT COST	TOTAL COST
	8 HOUR OPERATING DAY (PNEUMATIC CONVEYOR)		
4	Ice Crushers (36" x 84")	$108 K	$ 432 K
16	Blowers (6000 CFM)	10 K	160 K
16	Diesel Engines (450 HP)	52 K	832 K
4	Diesel Engines (150 HP)	17 K	68 K
28	Ice Collection Conveyors	8 K	224 K
4	Fuel Tanks (6300 gal)	3 K	12 K
4	Barges (150 T)	89 K	356 K
	Subtotal		$2084 K
	20% Margin		417 K
	Subtotal		$2501 K
1	Plow		30 K
4	Pipelines (18" IPS)		225 K
	TOTAL		$2756 K
	8 HOUR OPERATING DAY (CONVENTIONAL CONVEYOR)		
28	Ice Collection Conveyors	$ 8 K	$ 224 K
4	Barges (31 T)	18 K	72 K
	Subtotal		$ 296 K
	20% Margin		59 K
	Subtotal		$ 355 K
1	Plow		30 K
4	Conveyors (5' wide)		736 K
	TOTAL		$1121 K

Assumes 1 WTGB for 8 hr day.

TABLE 9.10 COST ESTIMATE FOR CLOGGED CHANNEL CLEARING SYSTEM FOR ST. MARYS RIVER AST'S HAUL TO AN ICE BOOM ON THE OUTSIDE OF EACH TURN

ALTERNATIVE 5

QUANTITY	COMPONENT	UNIT COST	TOTAL COST
	8 HOUR OPERATING DAY		
4	Ice Booms	$ 75 K	$ 300 K
4	Ice Collection Craft (AST's)	700 K	2800 K
	TOTAL		$3100 K
	24 HOUR OPERATING DAY		
4	Ice Booms	$ 75 K	$ 300 K
1*	Ice Collection Craft (AST's)	700 K	700 K
	TOTAL		$1000 K

* *Assumes 20 hours out of 24 hours removing ice or moving from turn to turn.*

9.2 Designs for the St. Lawrence River

For the St. Lawrence, there is one basic concept that has been expanded to 4 alternative designs. This concept is that of a barge containing ice collection conveyors and a conveyor on a rotating boom that can be pushed along the ice clogged channel, scooping up the ice and transferrring it to the adjacent ice cover. Alternative 6 is a single unit that would make one traverse of the 87 miles of ice clogged channel in 18 hours (a 24 hour operating day) at a speed of about 5 mph. Alternative 7 is three units similar to the single system, but smaller and working at a third the removal rate. Each would traverse one third of the river, making three passes at the same 5 mph speed, in a 24 hour operating day. Both alternatives were examined with and without ice crushers, assuming a maximum dimension of 3 feet for ice pieces.

The design removal rate is 37,000 ft^3/mile-day for 48 days in a severe winter. The transfer rate for equipment for a single unit system moving at 5 mph is, therefore, 185,000 ft^3/hr or 3083 CFM. A three unit system would require equipment of 1028 CFM on each system. The high transfer rates preclude the use of pneumatic conveyors so conventional conveyors are used in each alternative design.

Weight estimates for the barges for the single and three unit systems are presented in Tables 9.11 and 9.12, respectively. The rotating crane conveyor cannot be substantially reduced by adding an ice crusher to the single unit system because the volume flowrate requires the maximum conveyor speed presently in common use. On the three unit system, however, adding an ice crusher greatly reduces rotating boom size because the system without the ice crusher must have a boom the same size as the single unit system to accommodate the large ice piece size.

Tables 9.13 and 9.14 present the acquisition cost estimates for the four alternatives. A single unit system without an ice crusher is substantially cheaper than the other alternatives. The transfer rate or 3083 CFM is achievable with current technology.

TABLE 9.11 WEIGHT ESTIMATE FOR A SINGLE UNIT SYSTEM CLOGGED CHANNEL CLEARING BARGE FOR THE ST. LAWRENCE RIVER

ALTERNATIVE 6

QUANTITY	COMPONENT	UNIT WEIGHT	SYSTEM WEIGHT
	WITH ICE CRUSHERS		
3	Ice Crushers (36" x 84")	23 T	69 T
3	190 HP Diesel Engines	1 T	3 T
9	Ice Collection Conveyors (5' wide)	2 T	18 T
1	Rotating Crushed Ice Conveyor		42 T
1	Counterweight		36 T
1	Ballast Tank		3 T
1	Fuel Tank		2 T
8800 gals	Ballast Water		33 T
5000 gals	Fuel (8 day endurance)		16 T
	Ice Weight		28 T
	Subtotal		250 T
	20% Margin		50 T
	Subtotal		300 T
	500 T Barge L.S. Weight		177 T
	TOTAL		477 T
	500 T Barge (100' x 50' x 3.43')		
	WITHOUT ICE CRUSHERS		
	Subtotal (No Margin)		250 T
-3	Ice Crushers		- 69 T
-3	Diesel Engines		- 3 T
2900 gals	Increased Ballast (narrower vessel)		12 T
-2	Ice Collection Conveyors		- 4 T
	Change in Tankage		- 1 T
	New Subtotal		185 T
	20% Margin		37 T
	Subtotal		222 T
	350 T Barge L.S. Weight		126 T
	TOTAL		348 T
	350 T Barge (80' x 40' x 3.93')		

TABLE 9.12 WEIGHT ESTIMATE FOR A THREE UNIT SYSTEM CLOGGED CHANNEL CLEARING BARGE FOR THE ST. LAWRENCE RIVER

ALTERNATIVE 7

QUANTITY	COMPONENT	UNIT WEIGHT	SYSTEM WEIGHT
	WITH ICE CRUSHERS		
1	Ice Crushers (36" x 84")		23 T
1	190 HP Diesel Engines		1 T
5	Ice Collection Conveyors (5' wide)	2 T	10 T
1	Rotating Crushed Ice Conveyor		17 T
1	Counterweight		14 T
1	Ballast Tank		3 T
1	Fuel Tank		1 T
7800 gals	Ballast Water		29 T
1700 gals	Fuel (8 day endurance)		5 T
	Ice Weight		7 T
	Subtotal		110 T
	20% Margin		22 T
	Subtotal		132 T
	210 T Barge L.S. Weight		76 T
	TOTAL		208 T
	210 T Barge (80' x 30' x 3.12')		
	WITHOUT ICE CRUSHERS		
	Subtotal (no margin)		110 T
-1	Ice Crusher		- 23 T
-1	Diesel Engine		- 1 T
	Additional Rotating Conveyor Weight		25 T
	Counterweight Additional Weight		24 T
	New Subtotal		135 T
	20% Margin		27 T
	Subtotal		162 T
	250 T Barge L.S. Weight		89 T
	TOTAL		251 T
	250 T Barge (80' x 30' x 3.77')		

TABLE 9.13 COST ESTIMATE FOR A SINGLE UNIT SYSTEM CLOGGED CHANNEL CLEARING BARGE FOR THE ST. LAWRENCE RIVER

ALTERNATIVE 6

QUANTITY	COMPONENT	UNIT COST	TOTAL COST
	WITH ICE CRUSHERS		
3	Ice Crushers	$108 K	$ 324 K
3	Diesel Engines	22 K	66 K
9	Ice Collection Conveyors	8 K	72 K
1	Rotating Crushed Ice Conveyor		360 K
1	Ballast Tank (8800 gals)		4 K
1	Fuel Tank (5000 gals)		3 K
1	Barge		294 K
	Subtotal		$1123 K
	20% Margin		224 K
	TOTAL		$1347 K
	WITHOUT ICE CRUSHERS		
7	Ice Collection Conveyors	$ 8 K	$ 56 K
1	Rotating Crushed Ice Conveyor		360 K
1	Ballast Tank (12000 gals)		5 K
1	Barge		209 K
	Subtotal		$ 630 K
	20% Margin		126 K
	TOTAL		$ 756 K

Assumes availability of a tug of 5000 HP to push the barge.

TABLE 9.14 COST ESTIMATE FOR A THREE UNIT SYSTEM CLOGGED CHANNEL CLEARING BARGE FOR THE ST. LAWRENCE RIVER

ALTERNATIVE 7

QUANTITY	COMPONENT	UNIT COST	TOTAL COST
	WITH ICE CRUSHERS		
1	Ice Crusher		$ 108 K
1	Diesel Engine		22 K
5	Ice Collection Conveyors	$ 8 K	40 K
1	Rotating Crushed Ice Conveyor		220 K
1	Ballast Tank (7800 gals)		4 K
1	Fuel Tank (1700 gals)		1 K
1	Barge		126 K
	Subtotal		$ 521 K
	20% Margin		104 K
	TOTAL		$ 625 K
	TOTAL 3 SYSTEMS		$1875 K
	WITHOUT ICE CRUSHERS		
5	Ice Collection Conveyors	$ 8 K	$ 40 K
1	Rotating Crushed Ice Conveyor		360 K
1	Ballast Tank (7800 gals)		4 K
1	Barge		147 K
	Subtotal		$ 551 K
	20% Margin		110 K
	TOTAL		$ 661 K
	TOTAL 3 SYSTEMS		$1983 K

Assumes availability of a tug of 5000 HP to push the barge.

10. CONCLUSIONS AND RECOMMENDATIONS

The principal conclusion drawn from this study is that brash ice removal does appear to be effective and feasible at an acquisition cost of under $800 K. Removal on the St. Marys River should be limited to removal in the four turns, Striblings Point, Mirre Point, Johnson Point, and Winter Point, at a combined removal rate of 50,000 ft^3/day. Removal can be delayed until ice thicknesses reach approximately 31 inches. Systems on the St. Lawrence River should be designed to a removal rate of 37,000 ft^3/mile-day and 30 inches of ice can be allowed to form before removal begins.

Three Alternatives, Alternatives 2 and 5 for the St. Marys River and Alternative 6 with no ice crusher for the St. Lawrence River, should be considered in detail. Operational costs should be developed for these Alternatives so that life-cycle costing can be evaluated. The Alternatives are:

<u>2</u>: A WTGB transits the four turns of the St. Marys River each day making approximately 2 ice collection "loads" per turn. The WTGB has a plow that it uses to push a large volume (6400 ft^3/load) of brash ice to ice collection conveyors mounted on a barge near the middle of each turn. The WTGB must feed its load to the conveyors. The conveyors remove the ice from the water and transfer it to a long conveyor mounted on pilings. The ice is transported several hundred feet while being elevated to dump on a storage pile in shallow water (Figure 10.1).

<u>5</u>: An AST transits the four turns of the St. Marys River in a 24 hour operating day. At each turn, brash ice is scooped from the turn and dumped over an ice boom along the outside of the turn. The AST uses a front-end loader type bucket to lift and transport the ice. The vehicle would work its way around one turn and then proceed to the next turn (Figure 10.2).

<u>6</u>: A barge would be pushed down the length of the International Section of the St. Lawrence River, making one pass in 24 hours. The barge would house ice collection conveyors to scoop the ice from the water and a rotating boom conveyor to transfer the ice to the adjacent level ice cover. Ice would be removed at various points along the boom conveyor to provide an even distribution over 50 feet of the level ice on either side of the channel. Ice would be transferred to one side on an upbound passage and the other side on a downbound passage the next day (Figures 10.3 and 10.4).

Tables 10.1, 10.2, and 10.3 present the required data to determine operating costs and life-cycle costs. Acquisition costs of service spares have been estimated at 20 percent of system acquisition costs for machinery requiring maintenance. Down time can be provided by starting the system earlier in the winter but removing it at the same rate. The ice thickness for removal to start with 20 percent down time is shown in the tables.

EVALUATION

The entire study process was reviewed and the validity of the conclusions was found to depend upon:

1. The ice growth model
2. The ship performance model
3. The transit model
4. Several factors pertinent to specific designs:
    a. Ice piece size as far as need for icebreakers
    b. Capability of shorefast ice to support broken ice disposal along channel of St. Lawrence River
    c. The plow-performance of the WTGB
    d. The design feasibility of the AST in a loader configuration
    e. The feasibility of successfully applying the transfer techniques described (conveyors, etc.).

Confidence in the overall conclusions is a function of uncertainty in the factors identified above. The following recommendations are focused at reducing these uncertainties and therefore enhancing confidence and eventual successful *implementation.*

RECOMMENDATIONS

The brash ice growth model is based on the best information and data available. These data are quite limited however and there are no data at all at the very high traffic levels assumed in the math model. The effect of the traffic level itself was shown to be a second order effect above a threshold value. Revised traffic level projections will probably result from other studies, conducted by the Corps of Engineers, for example

Recommendation 1

The revised traffic projections should be reviewed with regard to their impact on this study.

Recommendation 2

The brash ice growth model should be validated with a controlled experiment in a particular reach by simulating high traffic levels with a frequent transit of a Coast Guard icebreaker. The brash ice thickness should be monitored along with meterological data. The ice growth model can then be "tuned" to provide validated results. This experiment can be coordinated with other related experimental objectives.

The ship performance model is based on model and full-scale test results. At this stage, no further study or data are recommended. If commercial ship performance is studied further for other reasons, for example model testing associated with a specific design, the results would be incorporated thereby refining the model.

The transit model is the culmination of several years evolutionary effort. No specific revision is recommended at this time. If, however, the model is refined for other purposes, the revision should be incorporated into an updated channel clearing model and the updated model exercised to update the conclusion of this study.

The ice piece size assumption is not crucial to the general conclusions. It does impact the costs, however, in that ice crushers were determined not to be a necessity based on the 3 ft maximum piece size. At low traffic levels it is known that pieces greater than 3 ft will exist. There are no hard data about piece size at very high traffic levels.

Recommendation 3

> A study of piece size is recommended to be included with the high traffic brash ice thickness study described above.

The weight of the broken ice distributed over the limited boom length from the channel clearing device must be supported by the fixed ice along the St. Lawrence River. It has been shown that 3.4 ft of ice distributed over 50 ft of the ice edge could be expected. It is known that the ice will deflect under any load. However, if the broken ice builds up gradually over the season, the fast ice may yield plastically or it may heal by freezing of small cracks.

Recommendation 4

> The ice sheet's ability to support this amount of broken ice must be verified by analysis and an experiment. It is recommended that an analytical approach be employed using whatever data are available.

The use of the 140' WTGB offers a very cost effective approach to channel clearing. In the analysis in this study several assumptions and approximations were used to project the WTGB's performance in pushing a brash ice plow. These assumptions are described in Appendix J. There are no model or full-scale data which directly apply to estimating ship's performance pushing a plow. Neither is there a fully developed analytical method to predict that performance.

Recommendation 5

A comprehensive model test program is recommended to determine the WTGB's performance in brash ice with a plow. It will be necessary to first complete a careful analysis of the phenomena involved to insure that proper modeling techniques are employed.

Archimedean Screw technology has been advanced to a fully functional prototype, as described in Appendix I. The craft's characteristics are ideally suited for operating in brash ice. While designs have been made of AST's to be employed as oil spill response craft in ice covered areas, no loader-type application has been designed.

Recommendation 6

It is recommended that a complete preliminary design of an AST, configured as a 3 ton loader,be developed. Detailed performance predictions and cost estimates should be included.

The materials handling technology applied in this study is a special application, but quite within the state-of-the-art. For example the self-unloading system for a 1000' Laker has a capacity of 11,200 T/hr, compared to 4790 T/hr required by the St. Lawrence River Alternative 6 system proposed. No study or design is recommended at this point in the materials handling field.

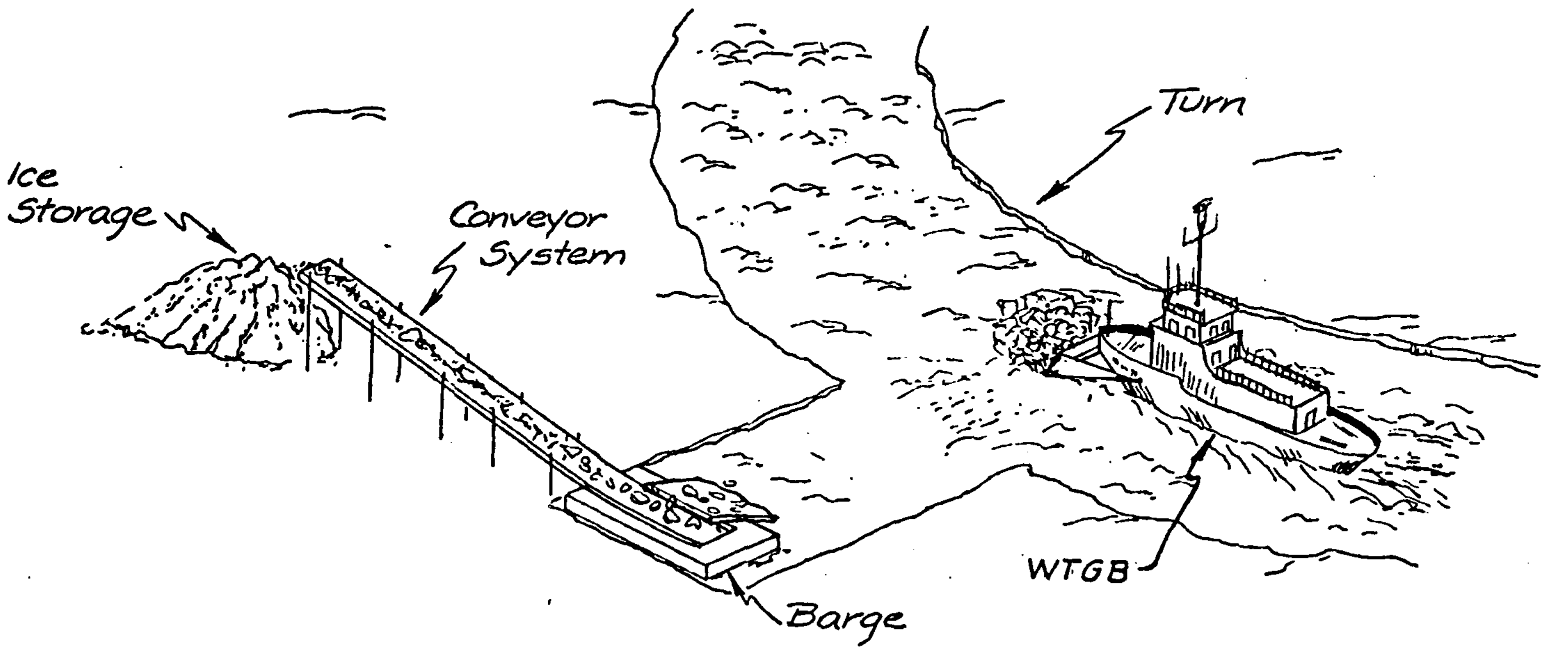


Figure 10.1. Concept for St. Mary's River Alternative 2

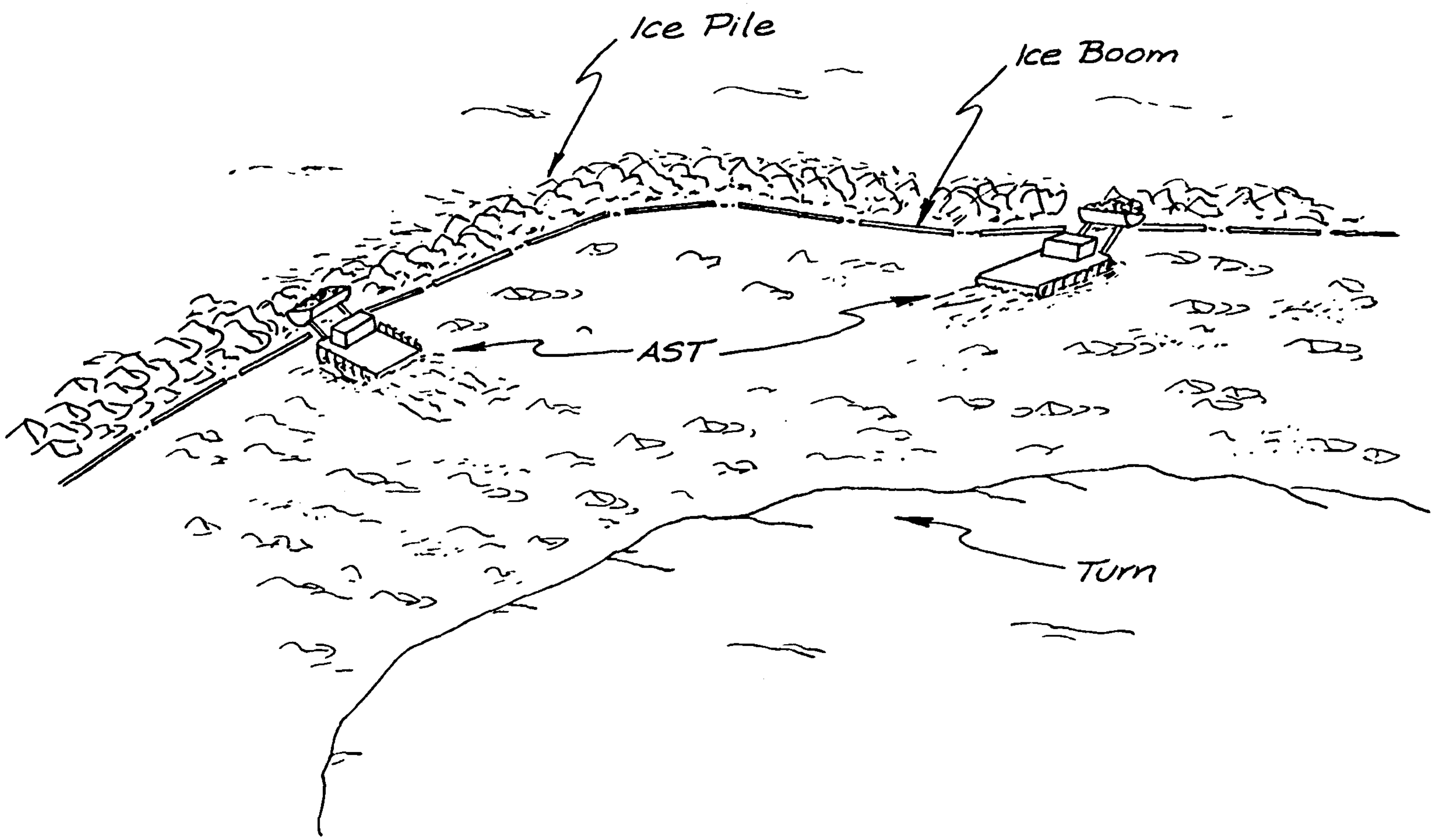


Figure 10-2 . Concept for St. Mary's River Design 5

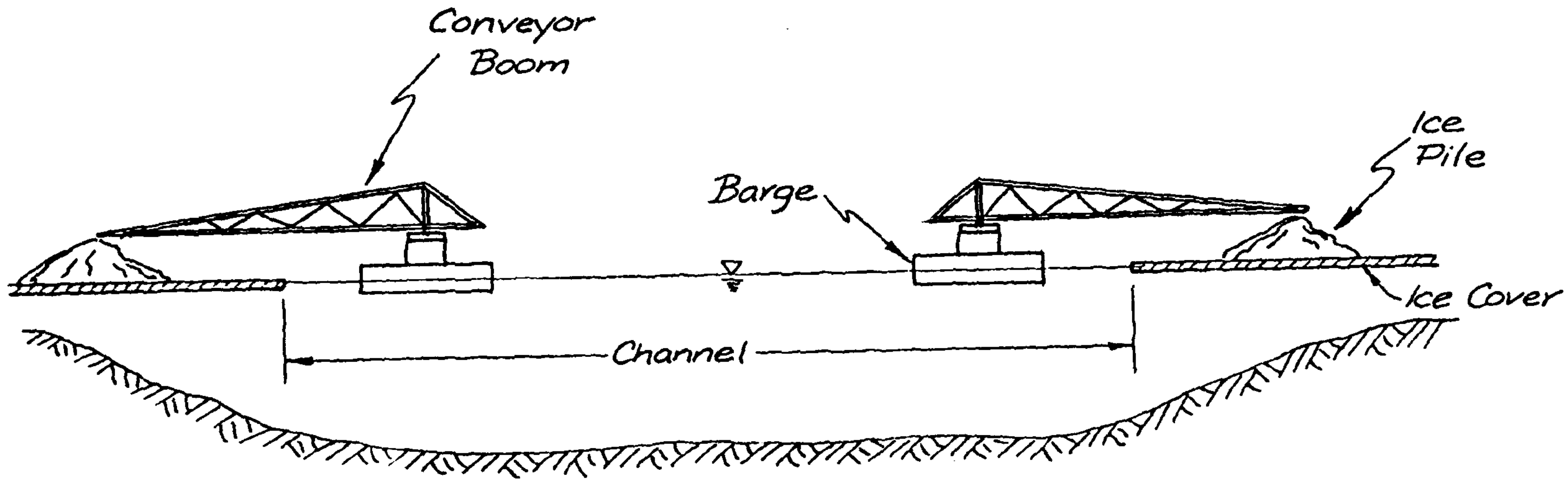


Figure 10.3. Concept for St. Lawrence River Alternative 6

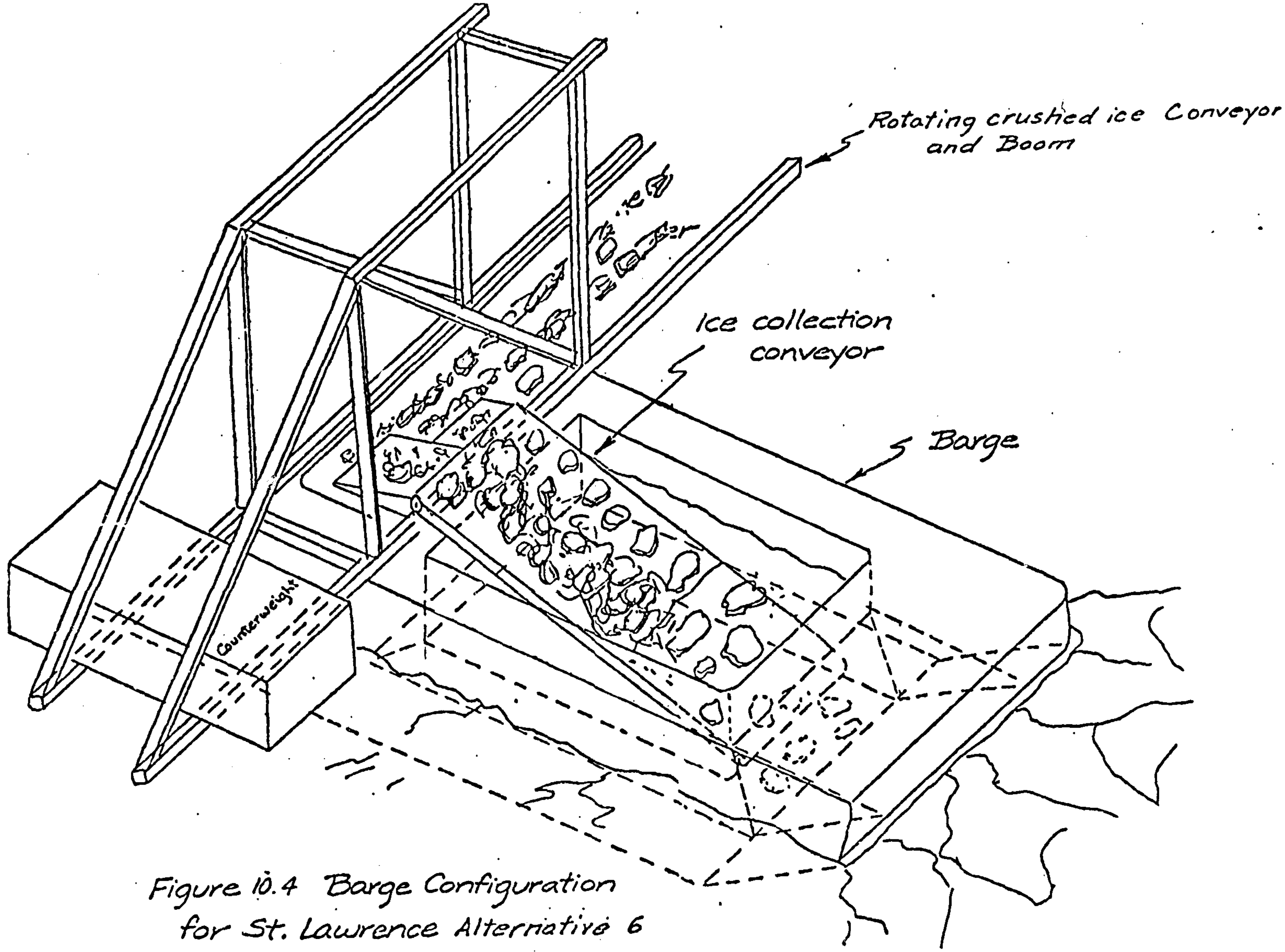


Figure 10.4 Barge Configuration
for St. Lawrence Alternative 6

AD-A104 671 ARCTEC INC COLUMBIA MD F/G 13/2
STUDY OF ICE CLOGGED CHANNEL CLEARING PROBLEMS.(U)
MAY 81 J W ST. JOHN, J L COBURN, T V KOTRAS DTCG38-80-C-80039
UNCLASSIFIED 569C-5 USCG-D-34-81 NL

AD A
104671

TABLE 10.1 ACQUISITION COSTS AND OPERATING PARAMETERS FOR ALTERNATIVE 2

QUANTITY	COMPONENT	TOTAL COST	HP	HRS/DAY OPERATING	MANNING
4	Ice collection barges	$355K	25 ea	2 ea	see conveyors
1	Plow	30K		8	----
4	Conveyors	736K	100 ea	2 ea	1*
	Service Spares	224K			
1	WTGB			8	

System starts at 23" of ice thickness — 80 operating days

Required operating days to meet severe winter removal — 66 operating days.

Days available for maintenance — 14 operating days.

* One man would be required to start machinery and monitor their operation. Could move from turn to turn on WTGB.

TABLE 10.2 ACQUISITION COSTS AND OPERATING PARAMETERS FOR ALTERNATIVE 5

QUANTITY	COMPONENT	TOTAL COST	HP	HRS/DAY OPERATING	MANNING
4	Ice booms	$ 75K	--	24	--*
1	AST	700K	780	24	2
	Service Spares for AST	140K			

System starts at 23" of ice thickness	80 operating days
Required operating days to meet severe winter removal	66 operating days
Days available for maintenance	14 operating days.

* Manpower and vessels will be required for deployment.

TABLE 10.3 ACQUISITION COSTS AND OPERATING PARAMETERS FOR ALTERNATIVE 6

QUANTITY	COMPONENT	TOTAL COST	HP	HRS/DAY OPERATING	MANNING
1	Ice collection and transfer barge	$756K	750	24	2
	Service spares	151K			
1	Pusher tug		5000	24	

System starts at 23" of ice thickness	58 operating days
Required operating days to meet worst removal	48 operating days
Days available for maintenance	10 operating days

11. REFERENCES

1. Ashton, G., "Evaluation of the Management Problems Associated with Operations of a Mechanical Ice Cutter on the Mississippi River", U.S. Army Cold Regions Research and Engineering Laboratory, Special Report 214, Oct., 1974.

2. Ashton, G. P., "River Ice", *Annual Review of Fluid Mechanics*, Vol. 10, 1978, pp. 369-392.

3. Berenger, P., and B. Michel, "Alogorithm for accelerated Growth of Ice in a Ship's Track", *Proceedings of the Third International Symposium on Ice Problems*, IAHR, Hanover, NH, 1975.

4. Comstock, J. P. (ed), *Principles of Naval Architecture*, Society of Naval Architects and Marine Engineers, 1974.

5. DeBord, F. W., "Analytical and Model Test Studies of the Maneuverability of Great Lakes Bulk Carriers in Ice Clogged Channels on the St. Marys River", Prepared for U.S. Department of Commerce, Maritime Administration, Contract No. 33623.

6. Greenwood, *Guide to Great Lakes Shipping*, Freshwater Press, Inc., Cleveland, Ohio, 1979.

7. Groh, D., Pickands Mather and Co., Personal Communication, May 1980.

8. Keinonen, A. and T. Nyman, "An Experimental Model-Scale Study on the Compressible, Frictional and Cohesive Behavior of Broken Ice Masses," *Proceedings of IAHR Symposium on Ice Problems*, Lulea, Sweden, Aug. 7-9, 1978, pp. 335-353.

9. Kim, J. K., and R. P. Voelker, "Test and Evaluation of Ice Transiting Bow Forms for Great Lakes Bulk Carriers," Prepared for the U.S. Maritime Administration.

10. Kotras, T. V., J. Kim, and J. Jacobi, "Great Lakes/St. Lawrence Seaway Lock Capacity Analysis", Prepared for U.S. Army Corps of Engineers, North Central Division, Report No. 478C-4, Contract No. DACW 23-78-C-0038, Chicago, IL, April, 1979.

11. Kotras, T. and J. Peter, "Computer Simulation of Great Lakes-St. Lawrence Seaway Icebreaker Requirements", Prepared for U.S. Coast Guard Academy, Report No. 296C-2, Contract No. DOT-CG-81-78-1953, June, 1979.

12. Lewis, J. W., et al., "Saint Lawrence Seaway System Plan for All-Year Navigation", Prepared for U.S. Department of Transportation, Saint Lawrence Seaway Development Corporation, Report No. 105C, Contract No. DOT-SL-73-360, July, 1975.

13. Lewis, J.W., et al., "Mathematical and Physical Modeling of Improvements to Ogdensburg-Prescott and Main Galop Booms to Allow Extended Season Navigation of St. Lawrence River Through 30 December", Prepared for U.S. Department of Transportation, St. Lawrence Seaway Development Corporation, Contract No. DOT-SL-76-467.

14. Major, R. A., "Model Tests in Ice to Confirm Effectiveness of the 140 ft WYTM Air Bubbler System," Prepared for U.S. Coast Guard, Office of Engineering, Contract No. DOT-CG-64,242A.

15. Mellor, M., "Towing Ships Through Ice-Clogged Channels by Warping and Kedging," U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Report 79-21, Prepared for U.S. Coast Guard.

16. Michel, B., *Ice Mechanics*, Les Presses De L'Universite Laval, Quebec, 1978.

17. Prodanovic, A., "Model Tests of Ice Rubble Strength", *Proceedings, Conference on Port and Ocean Engineering under Arctic Conditions,* Norwegian Institute of Technology, 1979, pp. 89-105.

18. Rumer, R. R. and R. D. Crissman, "Effect of Wind and Waves in Ice Transport in the Great Lakes", Prepared for U.S. Department of Commerce, Great Lakes Environmental and Research Laboratory, Contract No. 03-6-022-352636, June, 1977.

19. Sandkvist, J., "Accelerated Growth of Ice in Ship's Tracks Caused by Repeated Passages - Observation Results", University of Lulea, Division of Water Resources Eng., Internal Report 1979:07, Dec., 1979.

20. Uzuner, M. S. and J. F. Kennedy, "Hydraulics and Mechanics of River Ice Jams", Technical Report No. 161, Iowa Institute for Hydraulic Research, University of Iowa, Iowa City, Iowa, 1974.

21. VanBrunt, D., U.S. Steel Great Lakes Shipping, Personal Communication, May 1980.

22. Vance, G. P., "Preliminary Draft Summary, Characteristics of Ice in White Fish Bay and St. Marys River During January, February, and March 1979", U.S. Army Cold Regions Research and Engineering Laboratory, June,1979.

23. Vance, G. P., "Ice Clogged Channel Ice Disposal", U.S. Army Cold Regions Research and Engineering Laboratory, Prepared for Office of Research and Development, U.S. Coast Guard, Oct., 1979.

24. Voelker, R. P. and J. S. Friel, "Results of Ice Thickness Measurements on the St. Marys River at the End of the Great Lakes Extended Shipping Season," Prepared for U.S. Coast Guard, Report No. 174C, Contract No. DOT-CG-41516-A.

25. Welsh, J. P. and B. T. Kingsbury, "Characterization of Slush Ice on the Great Lakes", Prepared for Office of Research and Development, U.S. Coast Guard, Report No. CG-D-45-75, Nov., 1974.

26. Canada Hydrographic Service, "Sailing Directions, Gulf and River St. Lawrence," Second Edition, Department of the Environment, Ottawa, Canada, 1974.

27. U.S. Army Corps of Engineers, Detroit District, "St. Lawrence River Velocity and Flow Measurements," Great Lakes Hydraulics and Hydrology Branch, 1976.

28. NOAA, "United States Coast Pilot, Great Lakes: Lakes Ontario, Erie, Huron, Michigan, and Superior and St. Lawrence River," U.S. Department of Commerce, National Ocean Survey, April 1978.

29. U.S. Coast Guard, "Rules of the Road, Great Lakes," Department of Transportation, CG-172, July 1972.

30. U.S. Army Corps of Engineers, Detroit District, "Survey Study for Great Lakes and St. Lawrence Seaway Navigation Season Extension (Draft)," March 1979.

APPENDIX A

SUPPORTING DATA FOR THE SIMULATION MODEL

TABLE A.1 CHARACTERISTICS OF TURNS TO BE MAINTAINED DURING WINTER NAVIGATION

	AREA (ft^2)	RADIUS (ft)
Johnsons Point Turn	640,000	1785
Stribling Point Turn	819,000	3140
Winter Point Turn	790,000	3850
Mirre Point Turn	526,000	2315

Figure A-1 Frequency Distribution of Wind Speed on the St. Mary's River

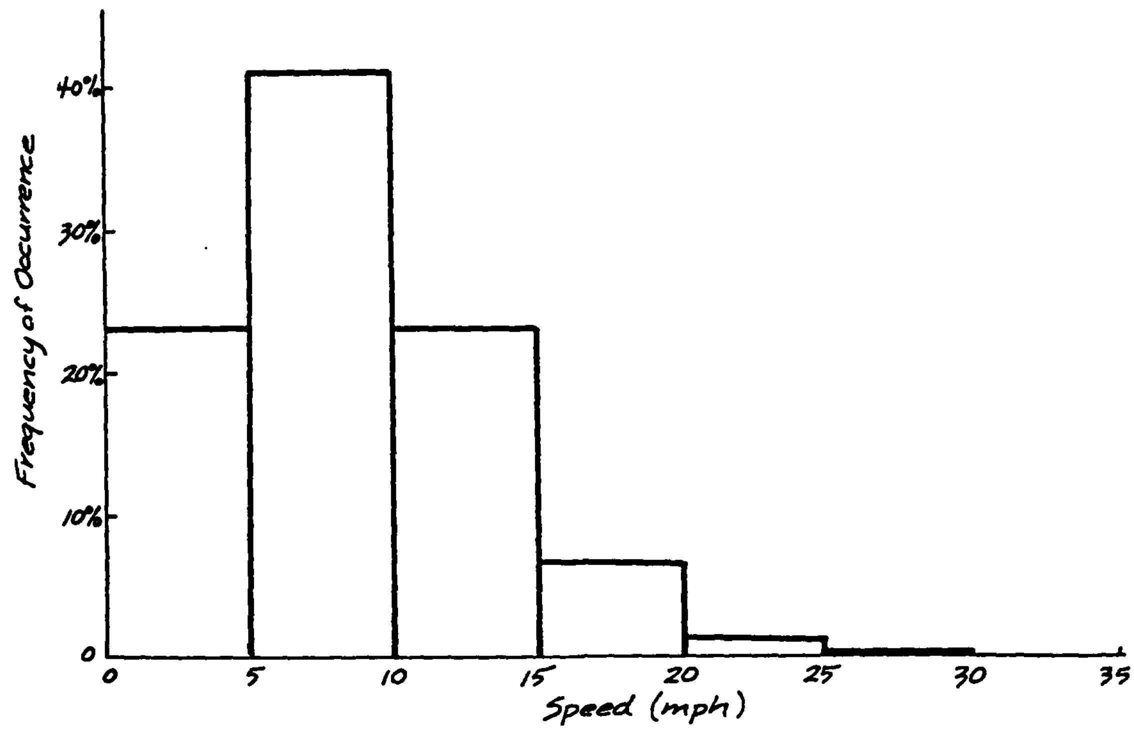


Figure A-2 Frequency Distribution of Wind Direction on the St. Mary's River

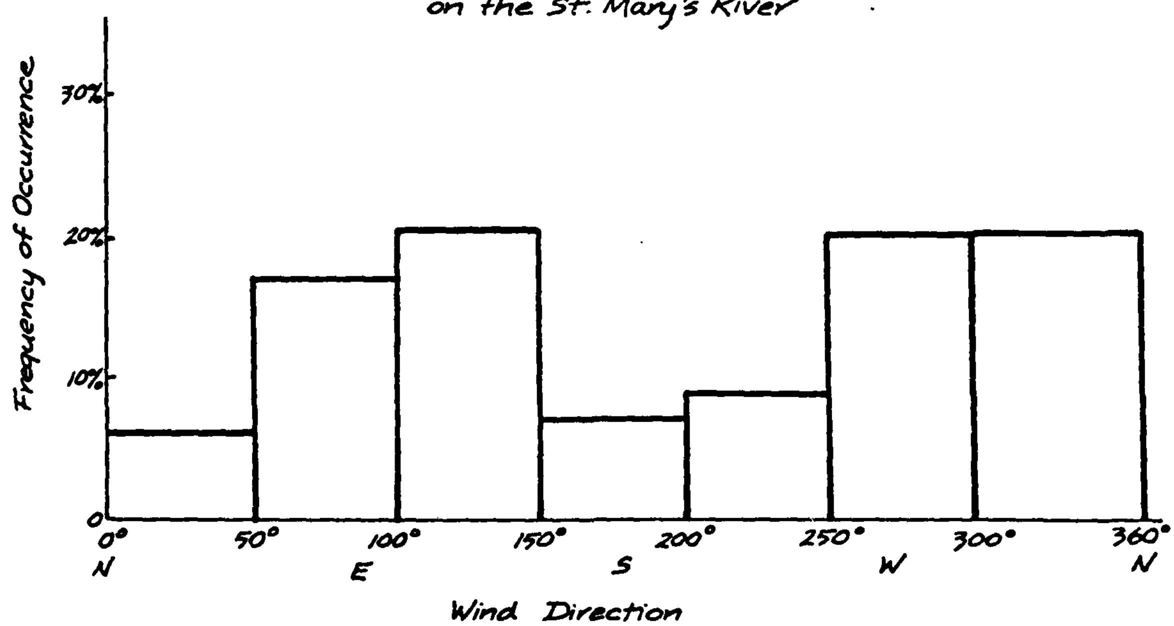


Figure A-3 Frequency Distribution of Wind Speed on the St. Lawrence River

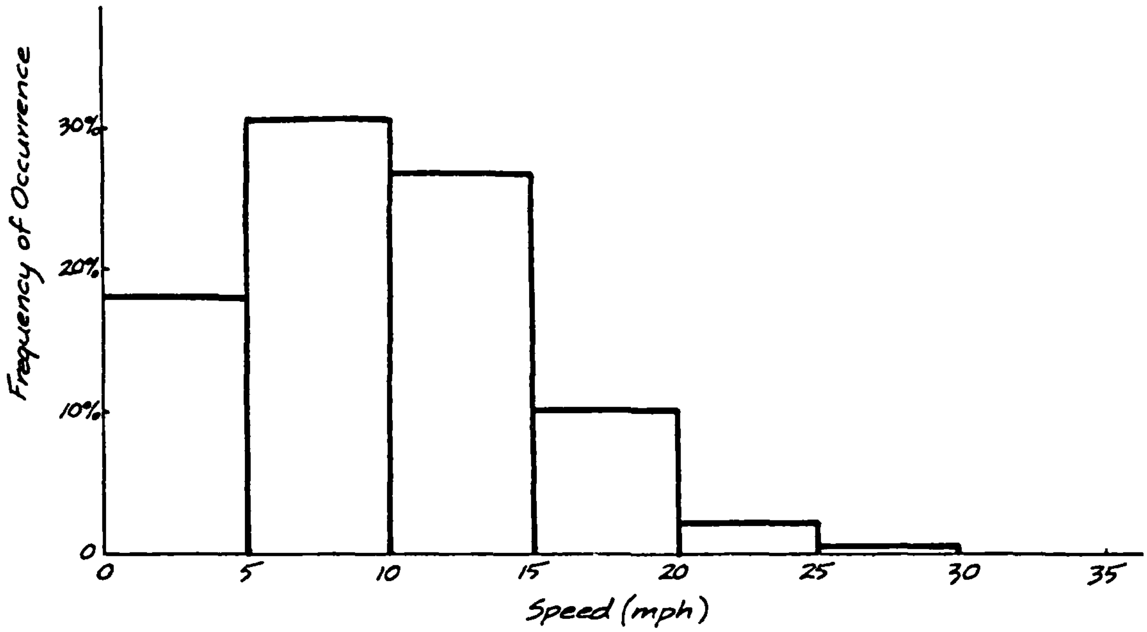
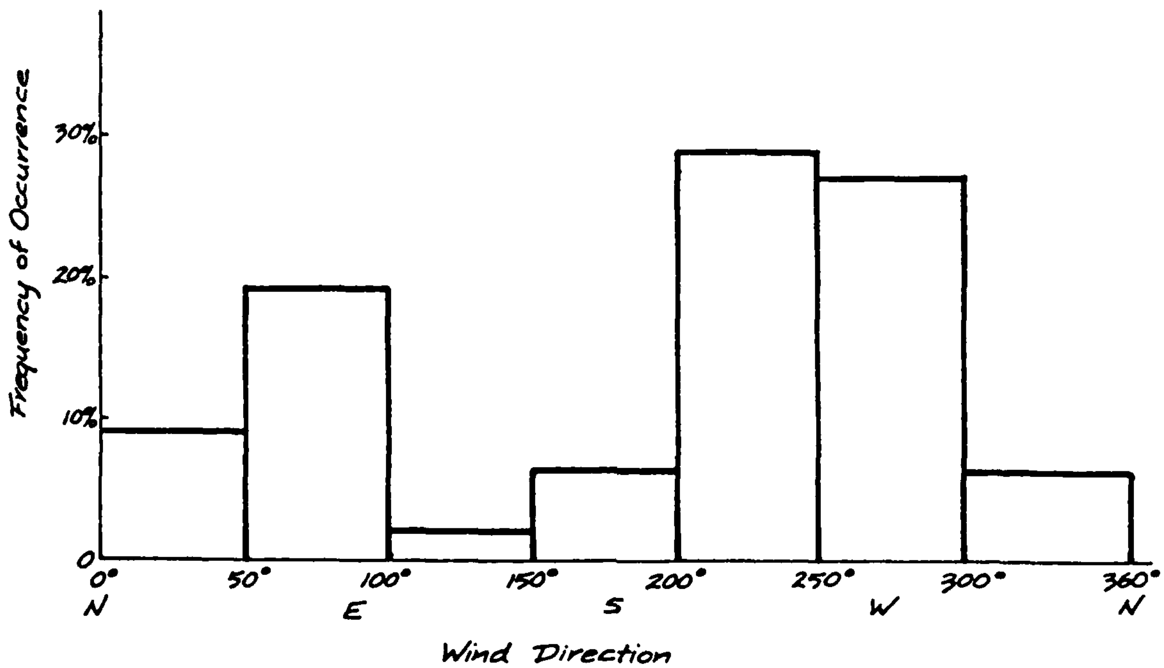


Figure A-4 Frequency Distribution of Wind Direction on the St. Lawrence River



Ice Growth Coefficients

The ice growth coefficient, α, and the porosity, β, for both the St. Marys River and the St. Lawrence River are:

	ST. MARYS RIVER	ST. LAWRENCE RIVER
Ice Growth Coefficient (α)	0.43	0.61
Porosity (α)	0.25	0.25

The values of α were obtained from field data for the St. Marys River [9] and from Reference [12] for the St. Lawrence River. The porosity, β, was taken from References [3] and [19].

TABLE A-2

CURRENT SEAWAY TRANSIT RESTRICTION (DRAFT AND POWER TO LENGTH RATIO)

Unique ice conditions are encountered in the St. Lambert-Iroquois segment. To reduce the problem of lengthy delays caused by vessels operating in ice, the following restrictions will apply during the 1979 closing period:

a) After 0001 hours on December 7, vessels in the following categories will not be accepted for transit between St. Lambert and Iroquois Locks:

Upbound - 1) Vessels with a power to length ratio of less than 20:1 (KW/meter) ~ 8.2 HP/FT.

2) Vessels with a forward draft of less than 40 dm.

Downbound - 1) Vessels with a power to length ratio of less than 15:1 (KW/Meter) ~ 6.1 HP/FT.

2) Vessels with a minimum forward draft of less than 20 dm.

b) After 0001 hours on December 12, vessels in the following categories will not be accepted for transit between St. Lambert and Iroquois Locks:

Upbound - 1) Vessels with a power to length ratio of less than 24:1 (KW/meter) ~ 9.8 HP/FT.

2) Vessels with a forward draft of less than 50 dm.

Downbound - 1) Vessels with a power to length ratio of less than 15:1 (KW/meter) ~ 6.1 HP/FT.

2) Vessels with a forward draft of less than 25 dm.

c) In all cases, the draft is to be sufficient to have the propeller fully submerged.

d) The draft limitations referred to in a) and b) do not apply to tugs.

e) Subject to approval, vessel operators may utilize a tug of a minimum of 3000 HP to augment the power of a vessel not meeting the requirements as specified above. In calculating the

TABLE A-2 (Continued)

vessel's power to length ratio, 50% of the tug's horsepower can be added to the vessel's power.

f) For determining the power to length ratio, the information contained in the Lloyd's Register will be used.

g) Vessel operators should note that the above restrictions are minimum and do not assure transit, and that the Seaway Entities may change the restrictions as ice conditions dictate. These changes will be announced as early as practical, but in no case later than 24 hours before they go into effect.

Ice Specifications

Ice Piece Size

Maximum ice piece dimensions were measured during ice trials of the Coast Guard Cutter (WYTM) in the winter of 1978-79. Tables A.3 and A.4 list the results of this investigation. Kingsbury and Welsh [25] investigated ice piece size of wind blown mush ice in Lake Michigan in the winter of 1973-1974. The distribution of ice piece size that they found are shown in Figure A.5. As it applies to this study, the results of their studies are not directly applicable to clogged channels in the St. Marys River or St. Lawrence Seaway since the dimensions of the ice pieces found in the icebreaker trials are the maximum ice piece dimensions that occur for a ship not operating repeatedly through the same track and the mush ice studied by Kingsbury and Welsh was formed by wind and waves. In the navigation channel, where ships are repeatedly breaking and rebreaking ice, one can expect the average piece size to be smaller. Based on visual observations of brash ice in the St. Marys River, the ice pieces in the center of the channel are mostly round and range up to approximately 2 or 3 feet in diameter. Along the sides of the channel the ice pieces tend to be more like those measured during the icebreaker trials.

Any channel clearing device or system must be able to handle ice pieces ranging in size up to 2 or 3 feet in diameter in the center of the channel and handle solid refrozen brash and level ice which must be broken up before removal along the sides of the channel. The channel clearing device or system must be able to break ice along the sides of the channel itself, or call upon an icebreaker to do it.

Ice Mechanical Properties

Vance [22] measured the mechanical properties of level ice in Whitefish Bay and the St. Marys River during the winter of 1978-79. Table A.5 lists the flexural strength, σ_f, crushing strength, σ_c, and elastic modulus, E, that he found. The channel clearing device must be able to handle the strongest ice likely to occur during the winter. These mechanical properties will occur when the ice is the coldest, which coincides with the greater removal rate requirements. For the purpose of this study, these properties may be assumed to exist in the St. Lawrence Seaway as well as the St. Marys River.

TABLE A-3 SUMMARY OF MAXIMUM ICE LENGTHS FOR TEST OF COAST GUARD CUTTER (WYTM)

			Bubblers Off				
			Ice Length, feet				
Run Number	Speed Knots	No. of Pieces	E(X)[a]	Std. Dev.[b]	Minimum	Maximum	Skewness[c]
3600	2.4	36	8.1	3.70	3.0	21.0	1.42
1100	0.98	54	34.3	13.16	14.0	70.0	.65
1300	1.94	54	32.3	16.21	9.5	78.5	.92
1110	5.40	85	25.8	11.87	8.5	66.0	1.27
1310	3.64	36	25.3	13.80	8.5	61.0	1.00
3430	11.4	20	14.2	7.67	4.5	27.0	.49
3530	11.6	19	10.4	4.11	5.0	16.0	.03
3610	10.8	36	9.4	4.46	3.5	23.5	1.28
1120	10.59	91	30.8	17.26	6.0	73.0	.64
1320	5.01	35	26.0	15.35	6.5	56.5	.71
1130	8.99	61	26.4	12.05	7.0	49.5	.51
1330	4.35	24	28.3[d]	11.13[d]	14.0	77.5	2.13

a Expected Length based on lognormal distribution of lengths
b Square root of Variance of length based on lognormal distribution
c Departure from normality (If Skewness is 0, the population is normally distributed)
d Goodness of fit of the lognormal distribution questionable, use of empirical CDF preferred.

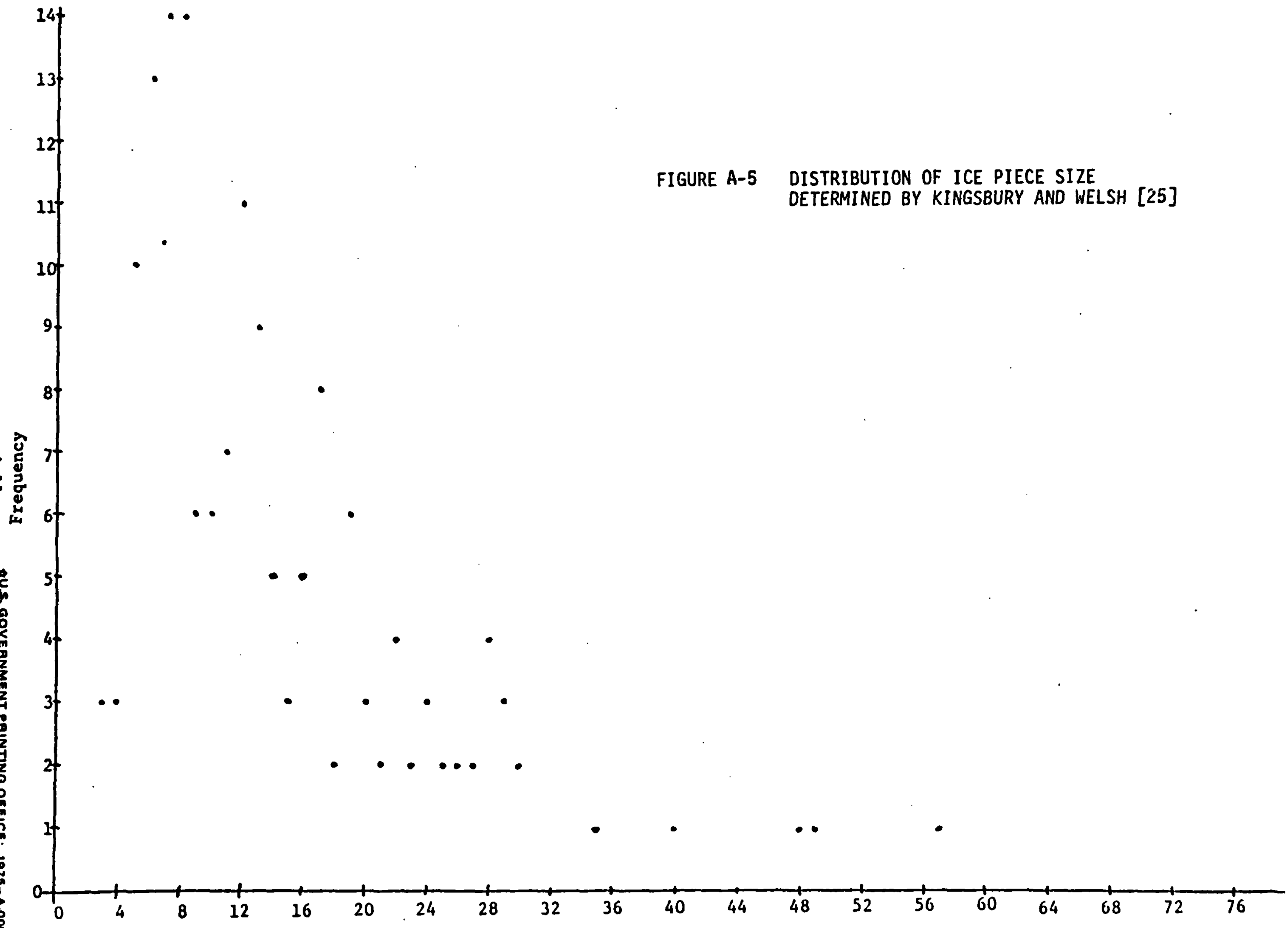
TABLE A-4 SUMMARY OF MAXIMUM ICE LENGTHS FOR TEST OF COAST GUARD CUTTER (WYTM)

Bubblers On

Run Number	Speed Knots	No. of Pieces	Ice Length, feet E(X)[a]	Std. Dev.[b]	Minimum	Maximum	Skewness[c]
4200	3.7	26	21.2	7.21	9.0	39.0	.77
4420	2.8	20	10.9	4.37	6.0	19.5	.78
1200	5.48	52	31.5[f]	20.78[f]	6.5	83.5	.90
2001	1.96	59	38.2	20.26	6.5	99.0	1.46
2100	2.98	41	31.3	16.76	7.5	93.0	1.66
2230	1.28	45	34.5	19.93	11.5	171.0	3.55
4210	7.50	18	22.6	10.49	9.0	46.5	.64
4310	8.9	34	10.3	4.42	3.5	18.0	.24
4410	-	21	7.5	3.60	4.0	23.0	2.06
2010	6.87	20	22.7	10.42	8.5	50.5	1.04
2110	7.47	38	25.4	15.61	5.5	61.0	.85
2221	4.7	30	22.4[f]	13.89[f]	4.0	59.0	1.44
1210	7.28	36	30.2	11.97	9.0	55.5	.12
2020	8.76	20	24.3	12.97	8.5	54.5	.95
2300	5.80	21	15.5	9.99	4.5	40.0	1.09
4330	12.8	41	10.1	4.45	4.5	31.5	2.10
2120	8.66	33	26.1[f]	16.05[f]	6.0	58.0	.67
1220	8.78	65	29.2[f]	16.24[f]	6.0	104.0	2.14
2030	10.45	59	26.2	13.61	8.5	63.0	.91
2130	8.54	39	30.0	13.92	9.5	80.5	1.78
2310	7.53	20	9.2	4.44	4.0	36.5	3.19
4300	12.7	37	14.3	7.55	4.5	36.5	1.01
4400	12.8	41	9.8	3.52	4.5	22.5	1.08
9000	-	18	27.8[f]	14.83[f]	11.5	53.5	.60

a Expected Length based on lognormal distribution of lengths
b Square root of Variance of length based on lognormal distribution of lengths
c Departure from normality (If Skewness is 0, the population is normally distributed)
d Brash Ice
e Forward and Aft
f Goodness of fit of the lognormal distribution questionable; use of empirical CDF preferred.

FIGURE A-5 DISTRIBUTION OF ICE PIECE SIZE DETERMINED BY KINGSBURY AND WELSH [25]



☆U.S. GOVERNMENT PRINTING OFFICE: 1975—A-0004

TABLE A-5 MECHANICAL PROPERTIES OF LEVEL ICE IN WHITEFISH BAY AND THE ST. MARYS RIVER FOR WINTER 1978-79.

MONTH	ICE TEMP.	σ_f (psi)	σ_c (psi)	E (psi)
Jan.	23°F	93	479	1.19×10^6
Feb.	18°F	103	537	1.23×10^6
Mar.	28°F	81	435	1.16×10^6

Unconsolidated brash ice obeys the Mohr-Coulomb relationship for a granular cohesive material:

$$T_f = C + N \tan\phi \tag{A.1}$$

where

T_f = Shear strength

C = Cohesive strength

N = Normal force

ϕ = Internal angle of friction

Prodanovic [17], and Keinonen and Nyman [8] conducted shear tests to determine the cohesive strength, C, and internal angle of friction, ϕ. Table A-6 lists their results. The stronger ice with the higher shear strength will be used in developing the design requirements for the clogged channel clearing system. Therefore, the cohesive strength will be taken as 0.82 psi and the internal angle of friction as 53°.

Ice Physical Properties

The weight density of ice used was 57.8 lbs/ft^3 giving a specific gravity of 0.92 for fresh water at a weight density of 62.4 lbs/ft^3 [12]. The angle of repose in air was taken as 47° and in water as 33° [28].

TABLE A-6 COHESIVE STRENGTH AND INTERNAL ANGLE OF FRICTION FOR ICE

Investigator	C (psi)	ϕ
Prodanovic	0.036 - 0.82	47° - 53°
Keinonen and Nyman	0.002	47°

APPENDIX B

DEVELOPMENT OF THE THEORY FOR THE MATHEMATICAL MODEL

B.1 BRASH ICE GROWTH IN NAVIGATION CHANNEL

The growth or accumulation of brash ice in the navigation channels of the St. Marys River and the St. Lawrence River can result from freezing which occurs between each ship transit and/or from jamming due to drag on the brash ice associated with the river current or wind velocity. Each of these are discussed in the following subsections.

B.1.1 Brash Ice Growth Due to Freezing

To estimate the thickness of the brash ice in the shipping channels resulting from freezing between ship transits, a mathematical model was developed which predicts the thickness of the refrozen and unconsolidated brash ice using the air temperatures, ship transit frequency, and ice properties. This mathematical model is similar to those described in References [1] and [3] and was developed as part of the work described in Reference [11].

When a ship passes through an ice field it leaves a mixture of broken ice pieces and water in its track. If the air temperature is below freezing, the water at the surface in the spaces between the ice pieces will start to freeze. The crust, which forms at the surface, consists of old broken pieces frozen together by new ice and is referred to as refrozen brash ice. As succeeding vessels travel through the track left by previous ships they, in turn, break up the refrozen brash ice and mix it with the unconsolidated brash ice. Since each ship brings a quantity of water to the surface, the growth of ice in the ship track is accelerated over the growth of level ice, as along a river bank or in a lake. Figure B-1 depicts brash and refrozen brash ice in a ship track with level ice on both sides of the navigation channel.

The basic equation for the growth of level ice is [12]:

$$h_i = \alpha \sqrt{FDD} \qquad \text{(B.1)}$$

where

h_i = Level ice thickness (in)

α = Growth coefficient $(\text{in}^2/°\text{F-Days})^{1/2}$

FDD = Cumulative freezing degree days (°F-Days)

The ice growth coefficient, α, varies from location to location and year to year, and is usually derived empirically from historical data using air temperatures and ice thickness. To be applied to the growth of refrozen

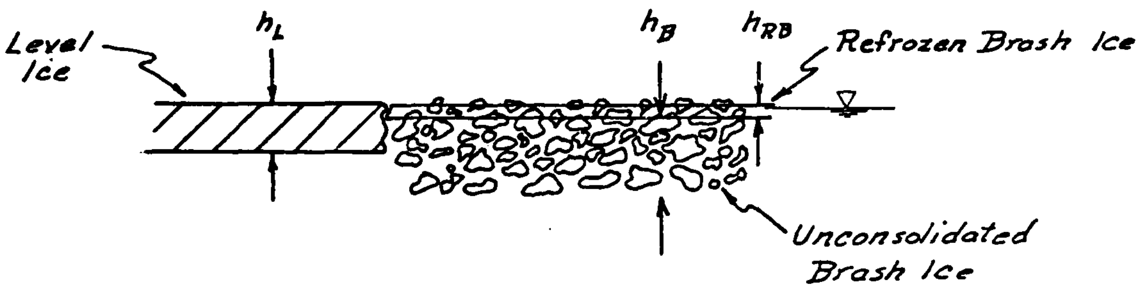


Figure B.1. Broken and Refrozen Ice in a Ship Track brash ice, Equation (B.1) can be modified as follows. If NS_i is the number of ships that traverse the channel in period i, and FDD_i is the number of cumulative freezing degree days in period i, then the average thickness of the refrozen brash ice, h_{R_i}, that each ship will experience in period i is:

$$h_{R_i} = \alpha \left(\frac{FDD_i}{NS_i} \right)^{1/2} \tag{B.2}$$

The unconsolidated brash ice is a mixture of solid ice pieces and voids filled with water. The porosity, β, of the unconsolidated brash ice is defined by:

$$\beta = \text{porosity} = \frac{\text{volume of voids}}{\text{total volume}} \tag{B.3}$$

Immediately after a ship has passed through a level ice field, the total mass of ice in the ship track is the same as before the ship passage. However, the thickness of the ice-water mixture, h_B, the unconsolidated brash ice, is now:

$$h_B = \frac{h_i}{(1-\beta)} \tag{B.4}$$

By accounting for the accelerated growth of the ice due to freezing using Equation (B.2) and mixing of water and ice using the porosity concept of Equation (B.4), it is possible to develop an equation to estimate the ice thickness in a ship track for each successive ship transit. Using the approach outlined in Reference[11] for the growth and melting of refrozen and unconsolidated brash ice, Equation (B.4) can be expressed as:

$$\begin{aligned} D_{j+1} = \Bigg[\Bigg(& D_j + \frac{\beta}{(1-\beta)} \left((h_{ue_j}^2 + h_{R_j}^2)^{1/2} - h_{ue_j} \right) + \\ & \frac{\beta(1-\beta)}{(1-\beta)} \left(((h_{ue_j} + h_{R_j})^2 + h_{R_j}^2)^{1/2} - h_{ue_j} + h_{R_j} \right) + \\ & \frac{\beta(1-\beta)^2}{(1-\beta)} \left(((h_{ue_j} + 2h_{R_j})^2 + h_{R_j}^2)^{1/2} - (h_{ue_j} + 2h_{R_j}) \right) \Bigg)^2 + \left((h_{ue_j}^2 + h_{R_j}^2)^{1/2} - h_{ue_j}^2 \right) \Bigg]^{1/2} \end{aligned} \tag{B.5}$$

where D_j = depth of ice experienced by the jth ship and

h_{uej} = the thickness of ice above the waterline experienced by the jth ship

$$= D_j \ (1 - \rho_i/\rho_w) \ (1 - \beta) \tag{B.6}$$

h_{Rj} = the thickness of refrozen brash ice experienced by the jth ship (from Equation B.2)

The variable, h_{uej}, is the effective thickness of the unconsolidated brash ice resting completely above the waterline and represents the insulating layer of ice that retards the growth of the refrozen brash.

Melting of the unconsolidated brash ice is treated much the same as the melting of level ice would be. Since the temperature is above freezing, no refrozen brash ice can form and the unconsolidated brash ice melts according to:

$$h_{Bj+1} = h_{Bj} + (0.2187 \quad FDD_{j+1})/(1 - \beta) \tag{B.7}$$

B.1.2 Brash Ice Growth Due to Jamming

The foregoing ice growth model predicts ice thickness due to growth by freezing and does not account for increased thickness due to jamming of the ice by the river current and wind shear. Uzuner and Kennedy [20] predict the thickness of an unconsolidated ice cover (brash ice field) under the influence of river current and wind shear stress as follows:

$$h_B = \frac{-b - \sqrt{b^2 - 4ac}}{2c} \tag{B.8}$$

where

$$a = \frac{\tau}{2k_x \gamma_e d_n} \tag{B.9a}$$

$$b = \frac{\gamma' S_o - 2(C_i/w)}{2k_x \gamma_e} \tag{B.9b}$$

$$c = \frac{-C_o}{k_x} \cdot \frac{d_n}{W} \quad \text{(B.9c)}$$

and

τ = Combined wind and water shear stress

$\gamma_e = 1/2\ (1 - \rho_i/\rho_w)(1 - \beta)\rho_i g \cos\theta$

$d_n = \left(\frac{f_b\ V_w \cdot D^2}{8g\ S_o}\right)^{1/3}$

k_x = Stress coefficient

γ' = Specific weight of ice

C_i = Cohesion Strength

C_o = Shear stress coefficient

w = Channel width

S_o = Channel slope

V_w = Water velocity

f_b = Darcy-Weisbach river bed friction factor

g = Acceleration due to gravity

The shear stress, τ, may be computed from:

$$\tau = \frac{f_i}{8} \cdot \rho_w\ V_w^{\ 2} + K\ \rho_a\ V_a^{\ 2} \quad \text{(B.10)}$$

where f_i = Friction factors related to the ice

k = Drag coefficient

ρ_a = The density of air

V_a = The wind speed

Substituting the appropriate values for the variables, following Uzuner and Kennedy [20] for the river-induced shear, and Rumer and Crissman [18] for the wind-induced shear, the thickness of the ice is predicted to be much less than 1 foot for even the extreme condition of 4 feet per second water velocities and 50 mile per hour winds acting parallel to the direction of the river current. The brash ice generated by the ships will exceed this thickness a few days after air temperatures fall below freezing. Therefore, ice jamming due to current and wind drag is not important in determining the ice thickness in either the St. Marys River or the St. Lawrence Seaway over the course of a winter.

In addition to jamming due to water and wind drag, brash ice could also become thicker than that predicted by the growth model if the river current is strong enough to sweep the ice pieces beneath the ice cover. Ashton [2] has developed an equation to determine the maximum velocity, V_c, at which the ice pieces will be submerged by the current.

$$\frac{V_c}{\left[gh_i\ (1 - \frac{\rho_i}{\rho_w})\right]^{1/2}} = \frac{2\ (1 - \frac{h_i}{D})}{\left[5 - 3\ (1 - \frac{h_i}{D})^2\right]^{1/2}} \qquad (B.11)$$

For a dredged channel water depth, D, of 27 feet, a typical ice piece thickness of 6 inches and a relative ice density ρ_i/ρ_w of 0.92, the water velocity at which the ice will submerge is 1.5 feet per second. Comparing this water velocity with those given in Table 3.2, it is apparent that the ice may be thicker than that which would occur due to freezing alone.

From Ashton [2], the equation for the thickness of the brash ice cover due to submergence of the ice pieces is given by:

$$\frac{V_w}{\left[2gh_c\ (1 - \frac{\rho_i}{\rho_w})\right]^{1/2}} = (1 - \frac{h_c}{D}) \qquad (B.12)$$

The maximum water velocity in the St. Marys River is 3 feet per second. Although the maximum water velocity in the St. Lawrence River is shown to be 4 feet per second in Table 3.2, this water velocity only exists downstream from the ice booms in a region of the river where brash ice will never occur [13]. Therefore, a more realistic maximum water velocity where ice exists is also 3 feet per second. Substituting into Equation (B.12) a water velocity of 3 feet per second and a depth of 27 feet, the thickness of the ice cover is computed to be approximately 2 feet. As will be seen in the following sections, this level of brash ice does not slow down the ships enough to cause problems and occurs relatively early in all of the winters simulated. Therefore, thickening of the ice cover due to submergence of the ice pieces is not important in determining channel clearing requirements and will not be explicitly included in the model simulations.

B.2 Vessel Thrust and Resistance Prediction

To determine a ship's ability to travel through a channel clogged with brash ice, a mathematical model was developed in this section to estimate a ship's speed in a straight channel filled with brash ice and to determine the consolidated brash ice thickness at which a given ship will get stuck in the river. In the following section the mathematical model is described in detail.

For steady state motion in ice, the available thrust of a ship, $T(V)$, is equal to the ship's resistance, $R(V)$, where both the thrust and resistance are functions of the ship's speed:

$$T(V) = R(V) \tag{B.13}$$

To determine the straight-ahead thrust-speed relationship for a given ship, the propulsion system of the ship must be analyzed. The thrust-speed relationship for the two vessels chosen in this study can be approximated by [9]:

$$T(V) = [1.32 - 0.196\ (V/V_{\text{design}}) - 0.124\ (V/V_{\text{design}})^2]\ T_{\text{design}} \tag{B.14}$$

where

$$T_{\text{design}} = 550\ \frac{(P.C.)(\text{shp})}{V_{\text{design}}}$$

T = Thrust of ship (pounds)

T_{design} = Design thrust (pounds)

V = Speed of ship (fps)

V_{design} = Design open water speed of ship (fps)

$P.C.$ = Propulsive coefficient = $\eta_O \cdot \eta_R \cdot \eta_H \cdot \eta_T$

shp = Installed rated or shaft horsepower

η_O = Propeller efficiency = 0.57

η_R = Relative rotative efficiency = 1.0

η_H = $1\text{-}t/1\text{-}w$ = Hull efficiency = 1.0

η_T = Transmission efficiency = 0.98

The normalized thrust vs. speed relationship of Equation (B.14) is shown in graphical form in Figure B.2.

Resistance of a given ship is a function of the ship's characteristics, its speed, and the ice conditions (type and thickness). For the purposes of this simulation, the resistance of a given vessel is assumed equal to:

$$R_T = R_{OW} + R_{RB} + R_B \tag{B.15}$$

where

R_T = Total resistance (pounds)

R_{OW} = Open water resistance (pounds)

R_{RB} = Refrozen brash ice resistance (pounds)

R_B = Brash ice resistance (pounds)

As a first order approximation, the open water resistance, R_{OW}, is assumed to obey a velocity-squared relation passing through the design open water speed point:

$$R_{OW} = T_{\text{design}} \left(\frac{V}{V_{\text{design}}} \right)^2 \tag{B.16}$$

where

T_{design} = Design thrust required to overcome the resistance at design open water speed (pounds)

V_{design} = Design open water speed (fps)

From model and full-scale resistance tests of the RYERSON, a 730' bulk carrier, and the new 1000' bulk carriers, the resistance of ships in refrozen and unconsolidated brash ice can be estimated to be [11]:

REFROZEN BRASH ICE

For $h_{RB} > 1"$: $$R_{RB} = 0.8\rho_w gBh_{RB}^2 \left[(0.273 + 1.96\mu_0)(1 + 4.51f) + (0.0011 + 0.0116\mu_0^2/\eta_2)(1 + 2.92f) \left(\frac{V}{\sqrt{gh_{RB}}} \cdot \frac{\sigma_f}{\rho_w g h_{RB}} \right) \right] \tag{B.17}$$

For $h_{RB} < 1"$: $R_{RB} = 0.0$

BRASH ICE

$$R_B = \rho_w gBh_B^2 \left[0.320 + 1.51\mu_0 + \left(0.0369 + 0.0745 \frac{\mu_0^2}{\eta^2}\right) \frac{V^2}{gh_B} \right] \tag{B.18}$$

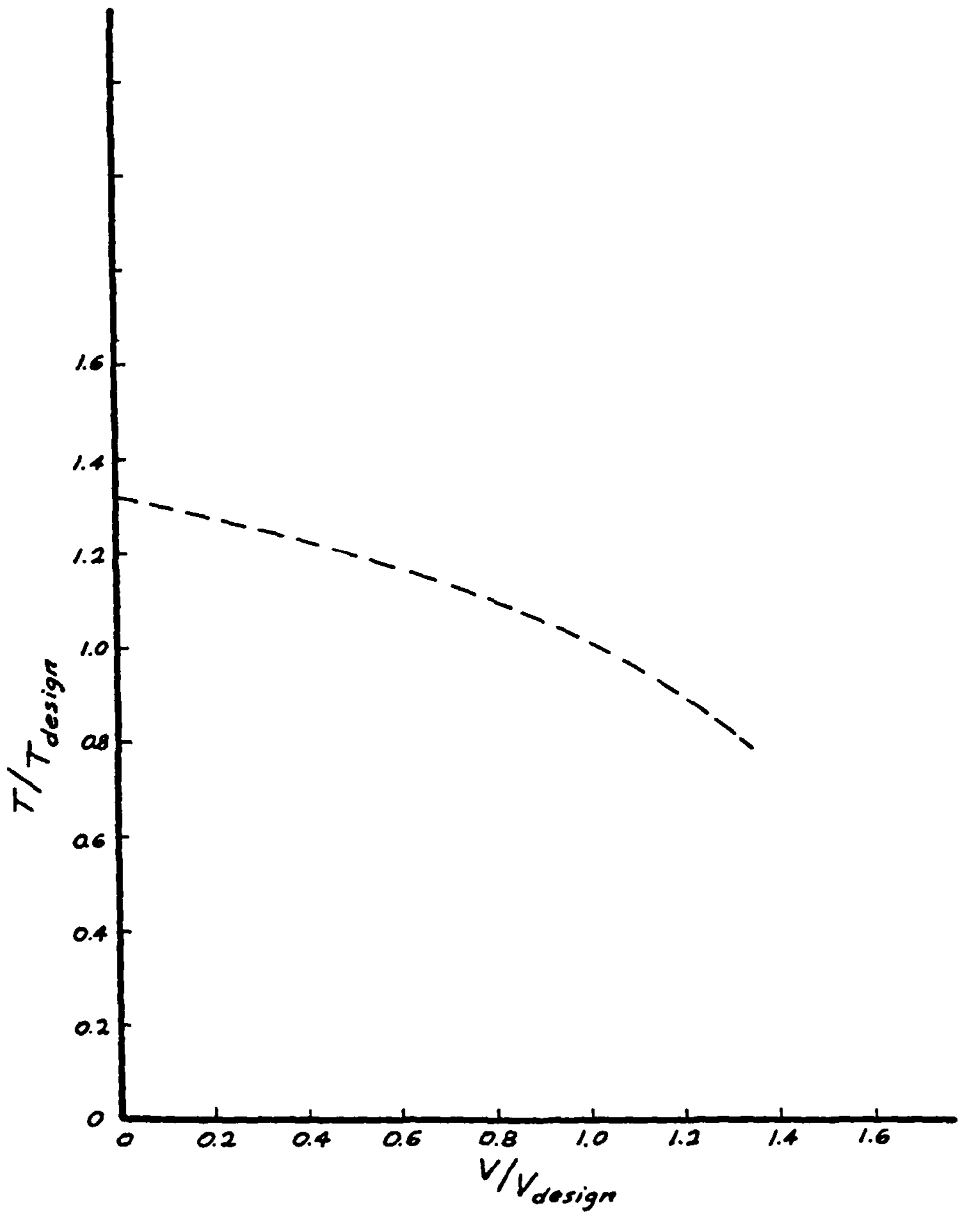


Figure B-2 Thrust - Velocity Relation

where B = Breadth of ship at waterline

g = Acceleration of gravity = 32.2 ft/sec

ρ_w = Mass density of water = 1.94 slugs/ft

σ_f = Flexural strength of ice = 18,000 psf

f = Hull-ice friction factor = 0.25

h_{RB}, h_B = Refrozen brash ice and unconsolidated brash ice thickness (ft)

μ_0 η_2 = Hull shape geometric coefficients obtained from analysis of vessel lines drawings (μ_0 = 5.56, η_2 = 1.94)

Since both $T(V)$ and $R(V)$ are of quadratic form, Equation (B.13) can be solved for the ship's maximum speed capability (V_{max}) using the standard quadratic formula. The procedure is illustrated graphically in Figure B-3. In solving this quadratic equation, two roots are obtained, consisting of positive and negative real roots, two negative real roots, or two complex roots, depending on the value of ice thickness for a given ship. If positive and negative real roots are obtained, the ship can proceed through the ice at a speed equal to the positive root, while the negative root is an extraneous solution to the equation. If two negative real roots or two complex roots are obtained, the ice is too thick for the ship to proceed through; that is, the ship does not have enough available thrust to overcome the resistance and its speed of advance will, therefore, be zero. In practice, a minimum speed of advance of approximately 2 mph exists below which ships will not proceed and can be assumed stuck. Thus, if V_{max} is less than 2 mph, the ship is assumed to be stuck in ice. Figure B-4 shows the relationship between V_{max} and brash ice thickness for the vessels considered in this study.

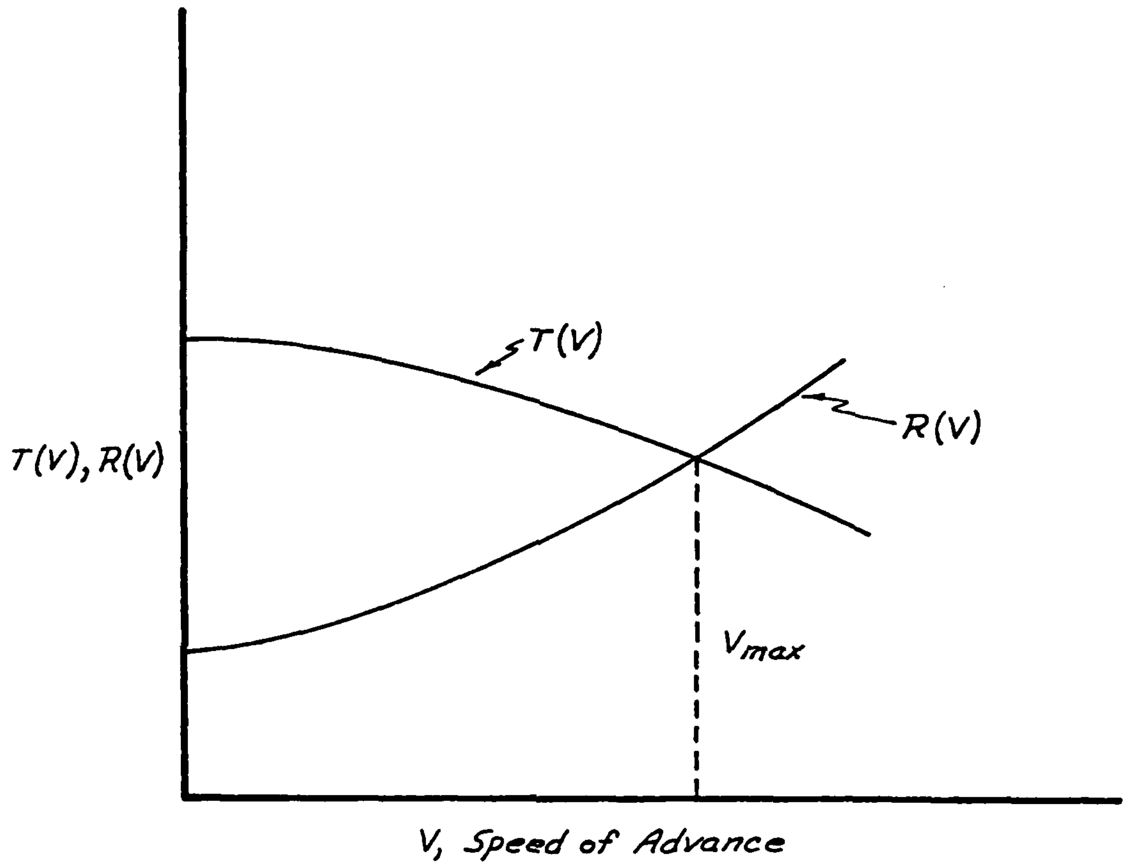


Figure B-3 Typical Thrust and Resistance Characteristics

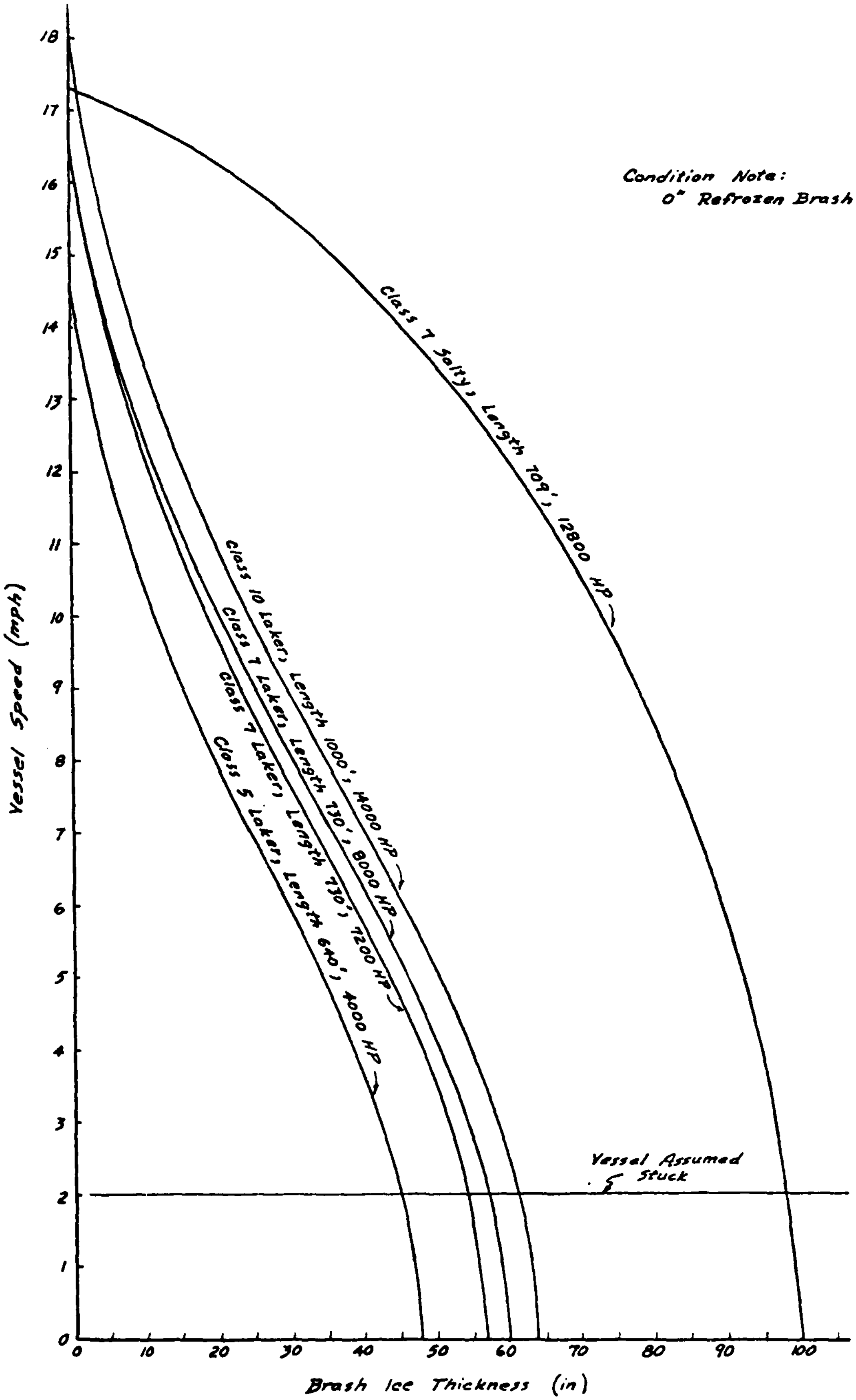


Figure B-4 Vessel Speed vs Brash Ice Thickness

B.3 Vessel Maneuvering in Brash Ice

B.3.1 Continuous Motion Through Turns

Ships experience additional difficulty when maneuvering around turns over and above that induced by brash ice resistance when traveling in a straight line. Brash ice limits ship maneuverability in two ways. First, ice degrades the turning performance of the ships and under certain conditions it becomes impossible to negotiate the turns without backing and filling. Secondly, ship resistance is increased in the turns due to the required rudder angle and the resulting side and angular velocities of the hull. Therefore, the limiting ice thickness for continuous operation in turns is significantly less than that in straight channel sections.

To assess the maximum brash ice thickness at which a ship may traverse a turn without backing and filling, a mathematical model was developed based on the linear equations of motion in yaw and sway for a ship maneuvering around a constant radius turn [4] using maneuvering model test results of a 1000' Great Lakes bulk carrier in open water and brash ice conducted for the U.S. Maritime Administration [5]. Of the two study areas, only the St. Marys River has turns sharp enough to cause significant difficulty for the vessels; therefore, the 1000' Laker was analyzed to predict the steady turning performance for three turns in the St. Marys River: Johnsons Point turn, Stribling Point turn, and Winter Point turn.

In summary, the linearized equation of motion in yaw and sway for a ship can be expressed as [4]:

$$(I_z' - N_{\dot{r}}')\,\dot{r}' - N_r'\,r' - N_v'\,v' = N_\delta'\,\delta \qquad \text{(B.19)}$$

$$(m' - Y_{\dot{v}}')\,\dot{v}' - (Y_r' - m')\,r' - Y_v'\,v' = Y_\delta'\,\delta \qquad \text{(B.20)}$$

where

$$I_z' = \frac{I_z}{(\rho/2)\ell^5} \qquad m' = \frac{M}{(\rho/2)\ell^3}$$

$$N' = \frac{N}{(\rho/2)\ell^3\ V^2} \qquad Y' = \frac{Y}{(\rho/2)\ell^2\ V^2}$$

$$N_r' = \frac{\partial N'}{\partial r'}, \qquad N_{\dot{r}}' = \frac{\partial N'}{\partial \dot{r}'}, \qquad N_V = \frac{\partial N'}{\partial V}, \qquad N_\delta = \frac{\partial N'}{\partial \delta}$$

$$Y_r' = \frac{\partial Y'}{\partial r'}, \qquad Y_V' = \frac{\partial Y}{\partial V'}, \qquad Y_{\dot{V}}' = \frac{\partial Y'}{\partial \dot{V}}, \qquad Y_\delta = \frac{\partial Y'}{\partial \delta}$$

$$r' = \frac{\ell}{R} = \frac{r\ell}{V}, \qquad \dot{r}' = \frac{\dot{r}\ell^2}{V^2}$$

$$v' = \frac{v}{V} = -\sin\beta, \qquad \dot{v}' = \frac{\dot{v}\ell}{V^2}$$

FORCES AND MOMENTS

X = Surge force

Y = Sway force

N = Yaw moment

SHIP MOTION

u = Surge velocity $\dot{u}$ = Acceleration (surge)

v = Sway velocity $\dot{v}$ = Side acceleration

r = Angular velocity $\dot{r}$ = Angular acceleration

V = Resultant speed

ℓ = Ship length

β = Drift angle

δ = Rudder control angle

A = Reference area = $\ell\, H$ or ℓ^2

R = Radius of curvature of path

M = Ship mass

I_z = Moment of Inertia in yaw

as depicted in Figure B.5

For a steady-state turn ($\dot{r} = \dot{v} = 0$), Equations (B.19) and (B.20) reduce to:

$$N'_r\, r' - N'_v\, v' = N'_\delta\, \delta' \tag{B.21}$$

$$-(Y'_r - m')\, r' - Y'_v\, v' = Y'_\delta\, \delta' \tag{B.22}$$

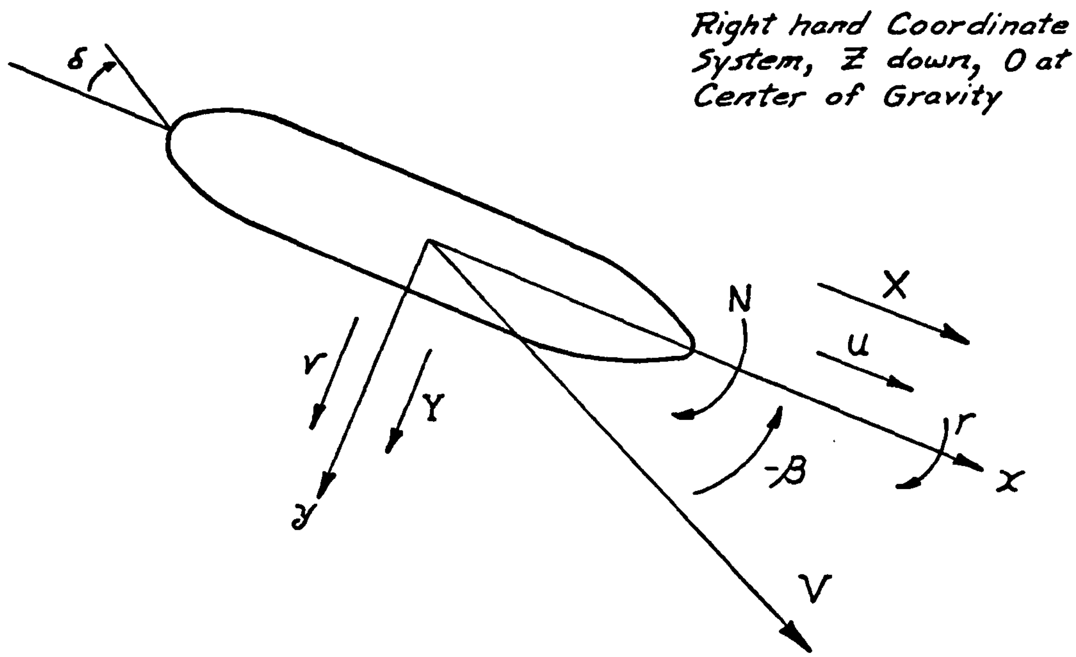
The simultaneous solution to Equations (B.21) and (B.22) yields:

$$\frac{1}{r} = \frac{R}{\ell} = -\frac{1}{\delta} \cdot \frac{Y'_v\, N'_r - N'_v\, (Y'_r - m')}{Y'_v\, N'_\delta - N'_v\, Y'_\delta} \tag{B.23}$$

$$v' = -\sin\beta = \delta \cdot \frac{N'_\delta\, (Y'_r - m') - N'_r\, Y'_\delta}{Y'_v\, N'_r - N'_v\, (Y'_r - m')} \tag{B.24}$$

where values for Y'_v, Y'_r, Y'_δ, N'_v, N'_r, and N'_δ were obtained from physical model test results [5].

Figure B.5. Free - Body Diagram of Ship Used for Maneuvering Around a Turn



Using Equations (B.23) and (B.24), the limiting brash ice thickness was then computed for each of the three turns which would allow the ship to maneuver through the turn in a continuous manner without having to back and fill. The limiting brash ice thicknesses were found to be 20 inches for Johnsons Point and Mirre Point Turn, 28 inches for Striblings Point Turn, and 30 inches for Winter Point Turn. It should be noted that this methodology is only concerned with establishing if vessels can maneuver around the turns without backing and filling. So long as vessels are able to go continuously around a turn, their transit time through the St. Marys River will not be greatly affected by the turns. However, if vessels must back and fill at turns, they may be considered effectively stuck since they will take a significant amount of time to negotiate the turn and have prevented other ships from traversing the river.

B.3.2 Vessel Maneuvering Around Turns with Backing and Filling

Previous analysis of vessel maneuvering around turns was limited to a 1000', 14,000 SHP Great Lakes bulk carrier negotiating four turns in the St. Marys River where the ship could proceed around the turn continuously without becoming stuck and having to back and fill. In this section, the above analysis was expanded to include the two additional vessels in the St. Marys River and the two additional vessels in the St. Lawrence Seaway. Also, the mathematical model used to predict maneuvering capabilities of the vessels was revised to permit transit time predictions for the condition when vessels must back and fill to negotiate the turns.

The method of analysis used to predict vessel performance through turns is summarized by the flowchart shown in Figure B.6 This approach was based on the linearized equations of motion in the horizontal plane as developed by Mandel [1]. In nondimensional form, assuming that the ship's center of gravity is located at the origin, the yaw and sway equations were expressed in the previous section (Equations B.19 and B.20).

The reduction and simultaneous solution to Equations (B.19) and (B.20) yield Equations (B.23) and (B.24). As illustrated in Figure B.6, the coefficients Y'_v, N'_v, Y'_r, N'_r, and N'_δ were estimated from results of physical model tests conducted for the U.S. Maritime Administration [2]. Using the results from these physical model tests, a set of coefficients was developed for each ship/ice condition/speed condition under consideration. It should be noted, however, that since model test data is not available for the 640' Laker or the Salty, coefficients for these hull forms were determined by assuming they were geometrically similar to the 730' Laker. Using these coefficients and the particular turn characteristics as input to Equation (B.23), the required rudder angle for the vessel to maneuver condintuously around the turn was calculated for each condition. If the rudder angle necessary to negotiate the turn in a continuous manner was greater than 45°, the turn radius which could be achieved with a 45° rudder angle was calculated. Next, the angle of attack (sway velocity) was calculated from Equation (B.24) and the total resistance of the ship in the turn was calculated:

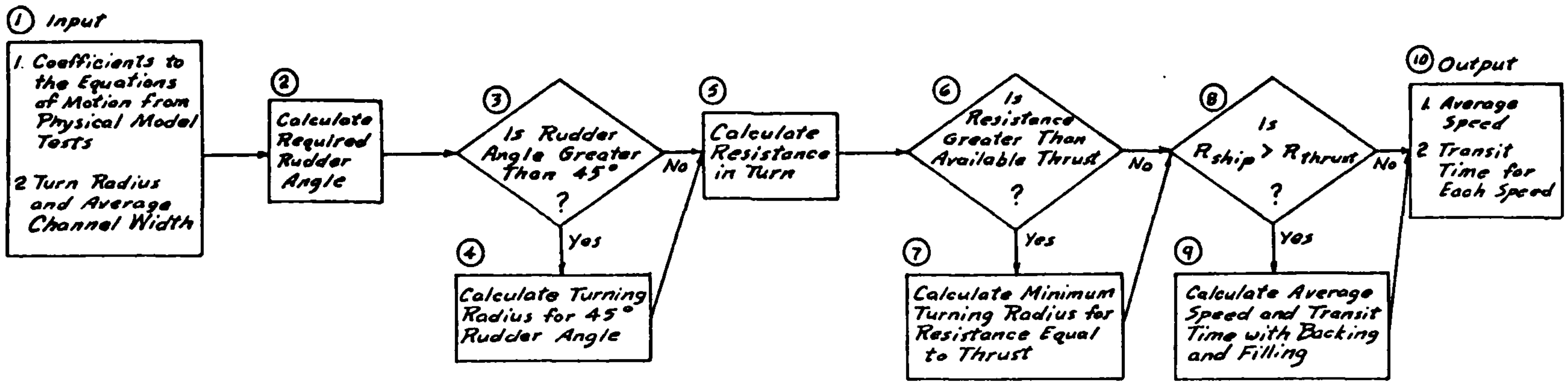


Figure B-6 Flowchart of Maneuvering Model

$$X'_T = X'_o + X'_\delta \delta + X'_v v' \tag{B.25}$$

where

$X'_T = X/\frac{\rho}{2}V^2\ell^2$ = Nondimensional total resistance

X'_o = Nondimensional resistance without turning

$X'_\delta = \partial X'/\partial\delta$ = Added resistance coefficient due to rudder angle

$X'_v = \partial X'/\partial v'$ = Added resistance coefficient due to angle of attack

and X_o was determined from the transit time model and X'_δ and X'_v were determined from model test data. This total resistance (X) was then compared to the maximum available thrust. If resistance exceeded available thrust, a new turning radius was calculated for the condition where thrust equaled resistance. This was accomplished by combining Equations (B.24) and (B.25) and solving for δ when $X'_T = T'_{max}$, and then solving for R using Equation (B.23).

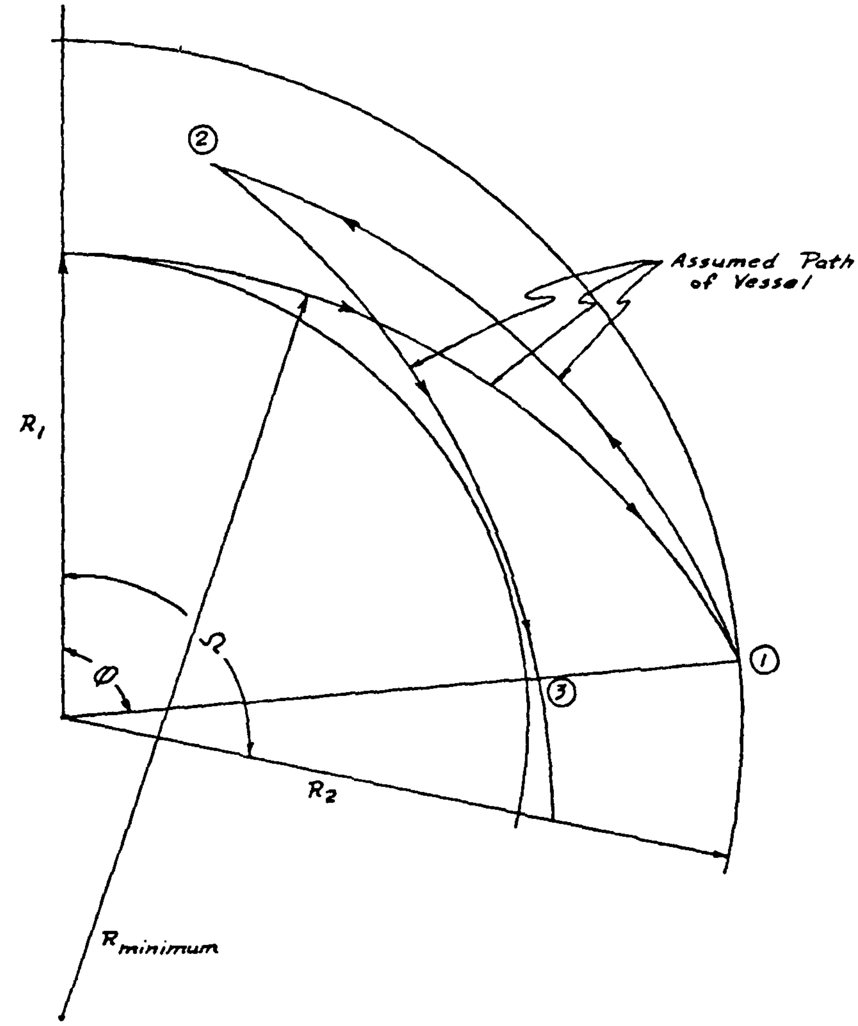
The output from the above analysis consisted of determining either: (1) required rudder angle, resulting angle of attack, and resistance for the ship negotiating the turn in a continuous manner; or (2) the minimum steady turning radius which could be achieved under the specific conditions considered. In the first case, minimum transit times for each ice thickness, ship, and turn were calculated directly. For the cases where the vessel turning radius exceeded the radius of the turn, a back-and-fill model had to be developed.

The assumed behavior for a vessel which must back-and-fill to negotiate a turn is shown in Figure B.7. The vessel enters the turn and proceeds at its minimum turning radius until it is within 1/2 of a beam of the outer channel edge as denoted by Point 1 in Figure B.7. The vessel then backs to a point denoted by 2 in Figure B.7 and changes heading such that it will be tangent to the inner channel (point 3 in Figure B.7) when it passes the angular position where it was originally forced to stop. The vessel then repeats this back-and-fill procedure until the entire turn is negotiated. The angle that the ship transits with each back-and-fill cycle, ϕ, can then be calculated geometrically as

$$\phi = 180° - \arccos\left(\frac{R_{min}^2 - R_2^2 - (R_{min} - R_1)^2}{-2R_2\,(R_{min} - R_1)}\right) \tag{B.26}$$

where R_1, R_2, and R_{min} are defined in Figure B.7. The number of required back-and-fill cycles is then calculated on the integer part of Ω/ϕ where Ω is the total angle of the turn, and the total transit time for the vessel to maneuver around the turn is given by:

$$T = \frac{\Omega\left(\frac{R_1 + R_2}{2}\right)}{V_{ship}} + A \cdot (T_B) \tag{B.27}$$



R_1 = Radius of Inner Edge of Dredged Channel + 1 Ship Beam
R_2 = Radius of Outer Edge of Dredged Channel − 1 Ship Beam
$R_{minimum}$ = Minimum Turning Radius of Vessel
Ω = Angle of Turn
φ = Angle Transited Before Vessel Must Stop

Figure B-7 Assumed Vessel Trajectory for Back-and-Fill Model where

A = Integer part of Ω/ϕ

T_B = Time for one back-and-fill cycle (sec)

V_{ship} = Resultant ship speed (ft/sec)

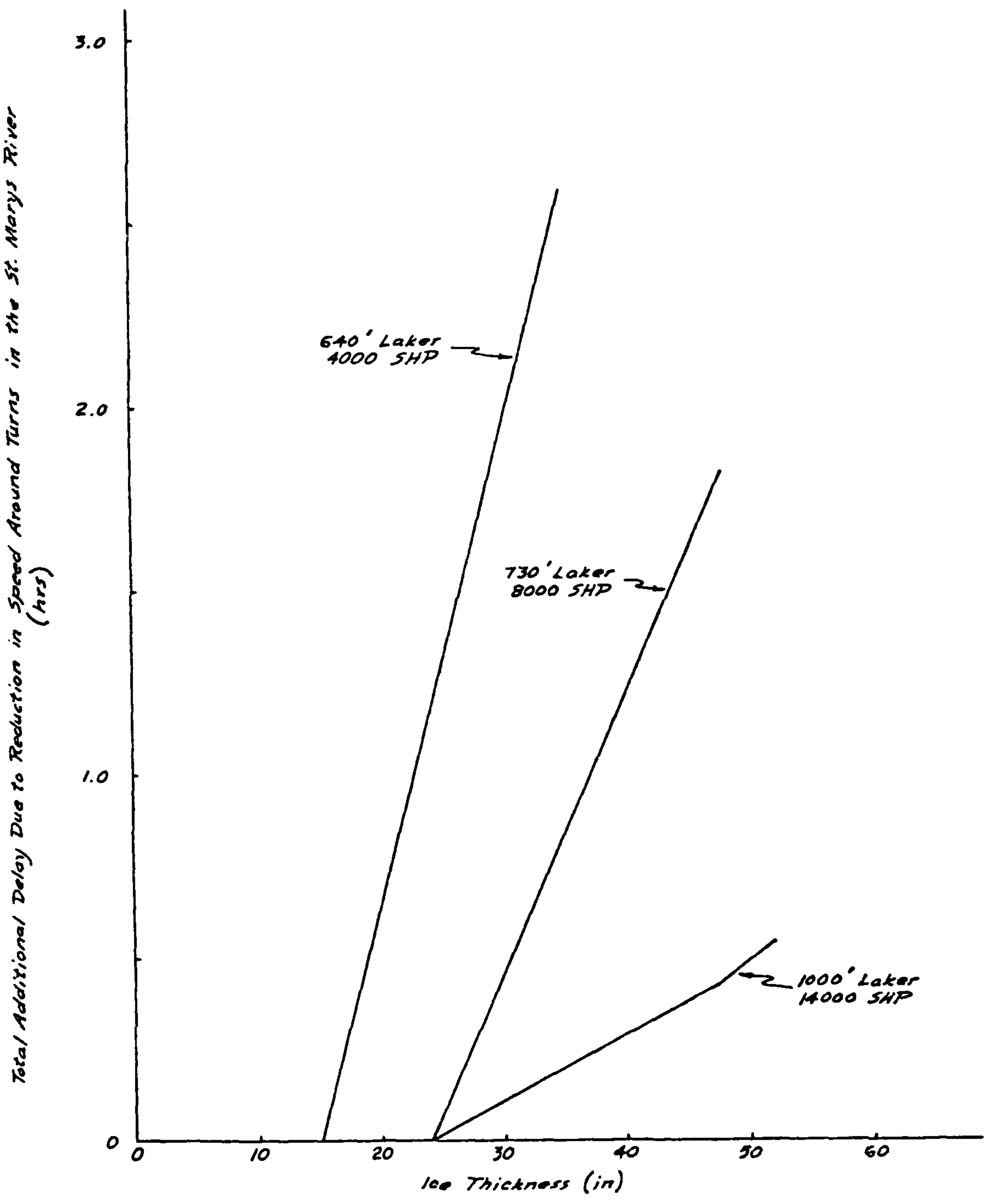
The time required for one back-and-fill cycle was estimated based on discussions with two fleet operators [3,10] and the back-and-fill model was checked by comparing results to the qualitative descriptions of these same operators. One operator [3] stated that any of the turns in the St. Marys River could be negotiated in 20 minutes under worst conditions. This included backing and filling twice. The second operator [10] stated that three backing and filling cycles would be required under worst conditions and the total time would be one hour. Therefore, T_B was set equal to 15 minutes and the model was exercised for a 1000' Laker negotiating Johnsons Point Turn in B-8 thick brash ice. Results indicated that the vessel would require one back-and-fill cycle and 21 minutes to negotiate the turn. If the broken channel width is restricted to 210' of the 300' wide channel the model predicts a transit time of 51 minutes with three back-and-fill cycles.

Results of this analysis conducted with the model as described above, for cases with infinite broken channel width, are summarized in Figure B-8 for the St. Marys River. The limiting brash ice thickness in turns for the 1000', 730', and 640' Lakers are 54", 48", and 35" respectively. At ice thicknesses greater than these, the ships cannot make progress around at least one of the turns, even with backing and filling. Delays in the turns do not occur for ice thickness less than 24" for the 730' and 1000' ships and ice thicknesses less than 15 inches for the 640' ship. For the turn in the St. Lawrence River around Carleton Island, the limiting brash ice thicknesses are 48" for the 730' Laker and 58" for the 709' Salty. Due to the relatively large channel width, the effective radius of the turn is large and significant delays do not occur at ice thicknesses less than these, provided the brash ice channel is sufficiently wide, on the order of three times the vessel beam.

B.3.3 Effect of Channel Width in Turns

The channel widths used in the simulation to compute the transit times through the four turns in the St. Marys River were taken to be the widths of the dredged channel. However, the actual width of the ice clogged channel, from level ice on one side to level ice on the other side, may not necessarily be that great. The channel width affects the vessel transit time in two ways. First the limitations of the narrow channel may require that the vessel back-and-fill in cases where the vessel turning radius is significantly greater than the average radius of the turn. The results of this type of maneuvering have been discussed in the previous section and have been incorporated into the results presented in Figure B-8. Secondly, the channel width may affect the vessel by changing the resistance that the vessel experiences as it moves through the turn, thereby slowing the vessel and increasing the minimum turning radius that the vessel can execute. As the channel becomes narrower the resistance to vessel motion increases as the brash ice is pushed against the hard level ice. As the channel width approaches the dimension of the ship's beam the level ice must be broken, which further increases the resistance. This effect has also been incorporated into the results of the previous section.

Figure B-8 Delay in Turns in the St. Marys River



Figures B-9 and B-10 show examples of the effect of channel width on the number of back-and-fill cycles required to maneuver around the turns and on the increase in resistance. The figures are for a 1000' Laker in 4 feet of brash ice for the four turns in the St. Marys River that are likely to cause problems. From these figures it is seen that for channel widths approximately three times the ship's beam, the number of back-and-fill cycles and the resistance to vessel motion do not change dramatically. However, for channel widths approximately twice the ship's beam, three (3) back-and-fill cycles are required for Johnsons Point, Striblings Point, and Winter Point Turns. For this reason, the channel width to be cleared in the turns was taken to be approximately 300 feet. In this manner, the impact of the vessel negotiating the turn and on vessels waiting to transit the turn can be minimized.

B.3.4 Effects of Ice Buildup at Outside of Turns Du[illegible] Ship Passage

Variations in vessel performance around turns due to ice buildup at the outside of the channel were investigated for the case of a 1000' Laker maneuvering around Johnsons Point Turn in infinitely wide 4.0' thick brash ice. The method of approach consisted of first determining the distribution of ice across the channel after the passage of a 1000' Laker and then predicting the performance of a 1000' Laker operating through this ice distribution. It should be noted that the analysis is theoretical and that neither the calculated ice distribution nor the predicted ship behavior have been documented with field observations or model studies.

The assumed ice behavior during and after the passage of a 1000' Laker through uniform brash is illustrated in Figures B-11 and B-12. As the ship passes through the turn with an angle of attack, β, ice is "plowed" to the outside of the channel and forms a berm along the side of the ship. The shape of the berm is governed by the angle of repose for ice which is assumed to be 33°, and the volume of ice in the berm is determined by conservation of mass between section AA and BB as shown in Figure B-11. After the ship has passed, the berm is unstable and ice that was against the ship's side floats to the open water area until the slope of the berm is equal to the angle of repose. It is assumed that this ice which floats into the open water channel is distributed uniformly as illustrated in Figure B-12. The dimensions of the ice distribution shown in Figure B-12 are determined as follows:

$$X_1 = L \sin\beta + B \cos\beta \tag{B.28}$$

where

L = Ship length

B = Ship beam

β = Angle of attack

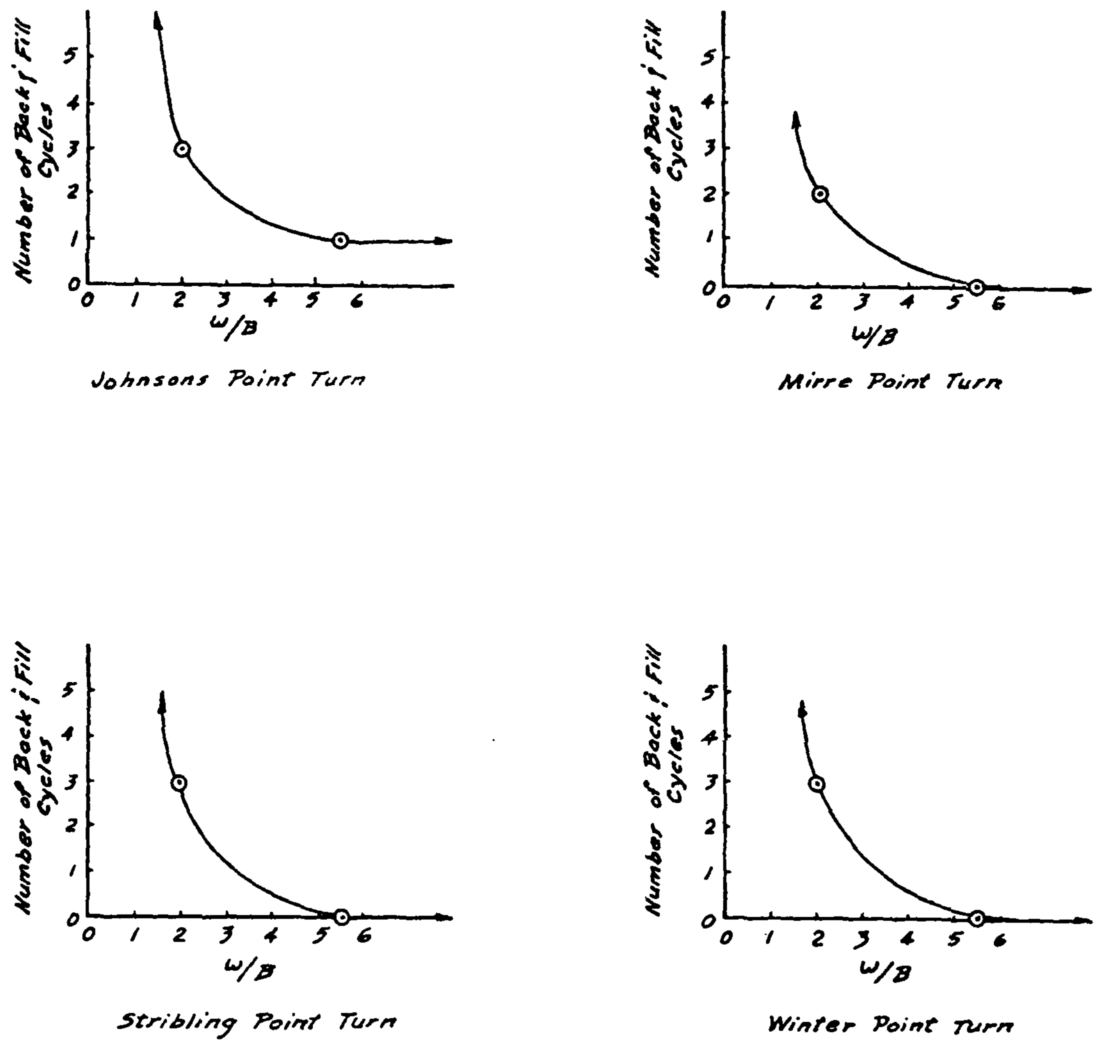


Figure B-9 Number of Back-and-Fill Cycles for 1000' Laker in 4' Brash Ice for Turns in the St. Marys River

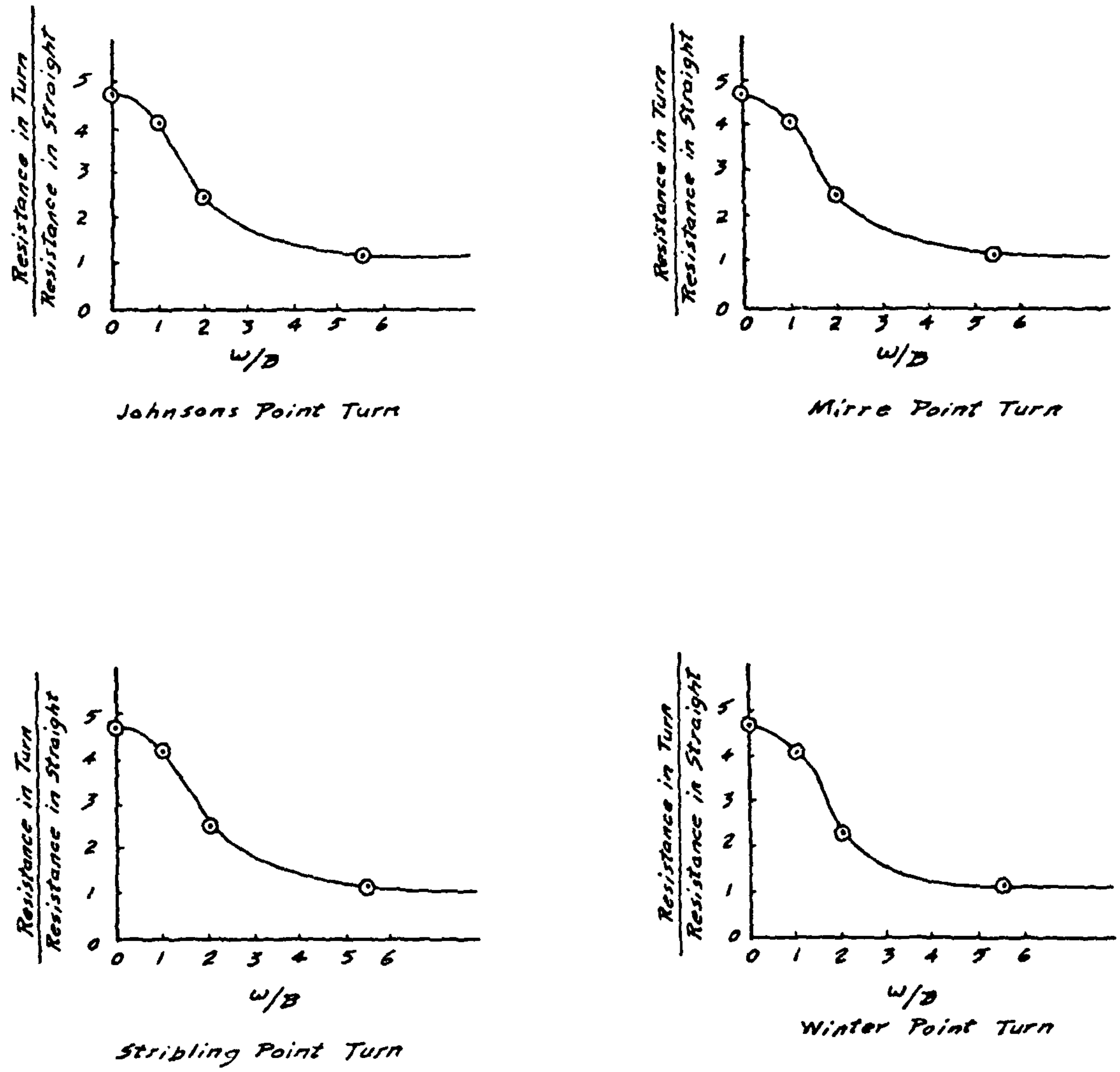


Figure B-10 Ship Resistance in Turns for 1000' Laker in 4' Brash Ice in St. Marys River

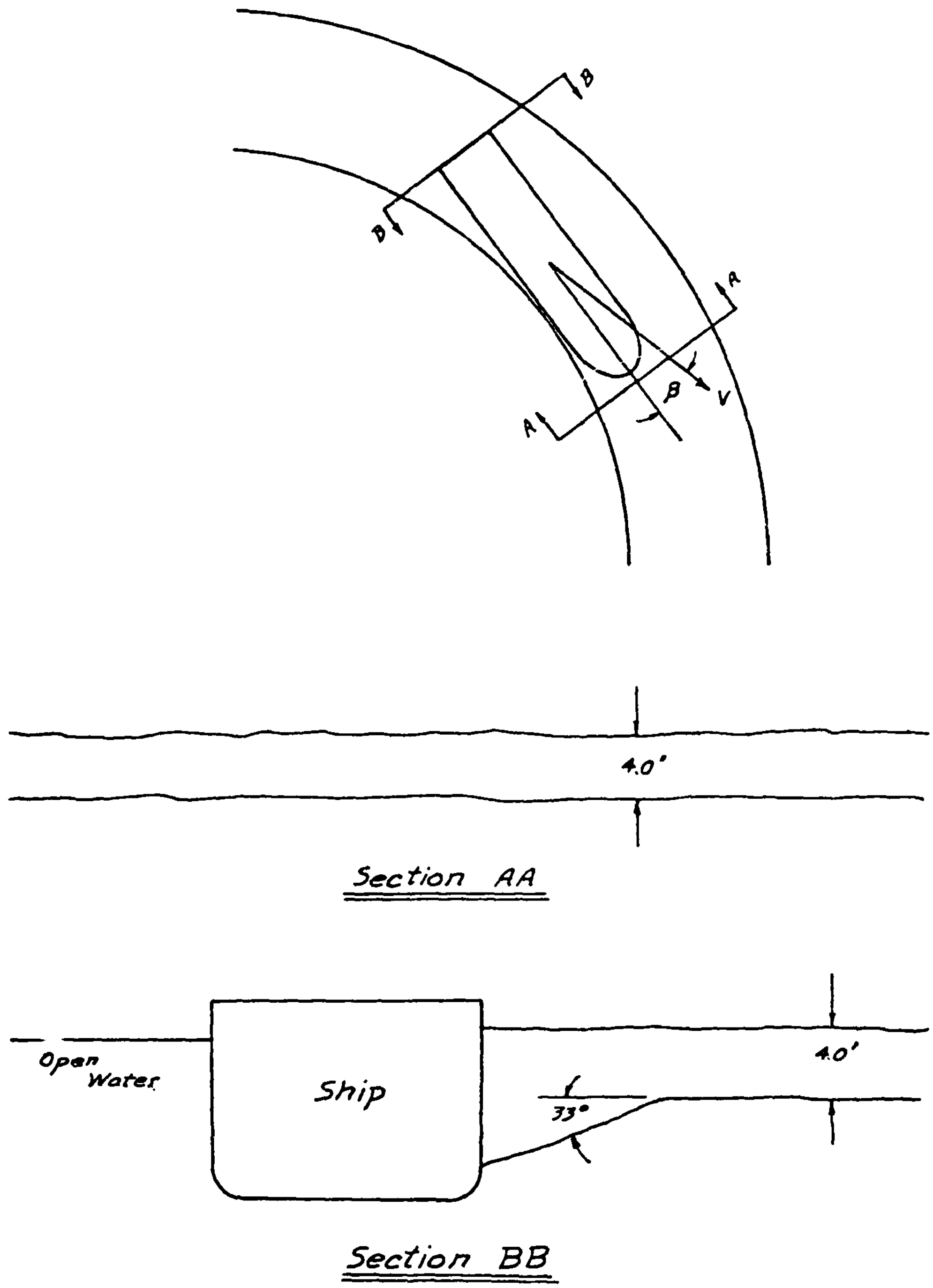


Figure B-11 Assumed Ice Behavior as Ship Passes

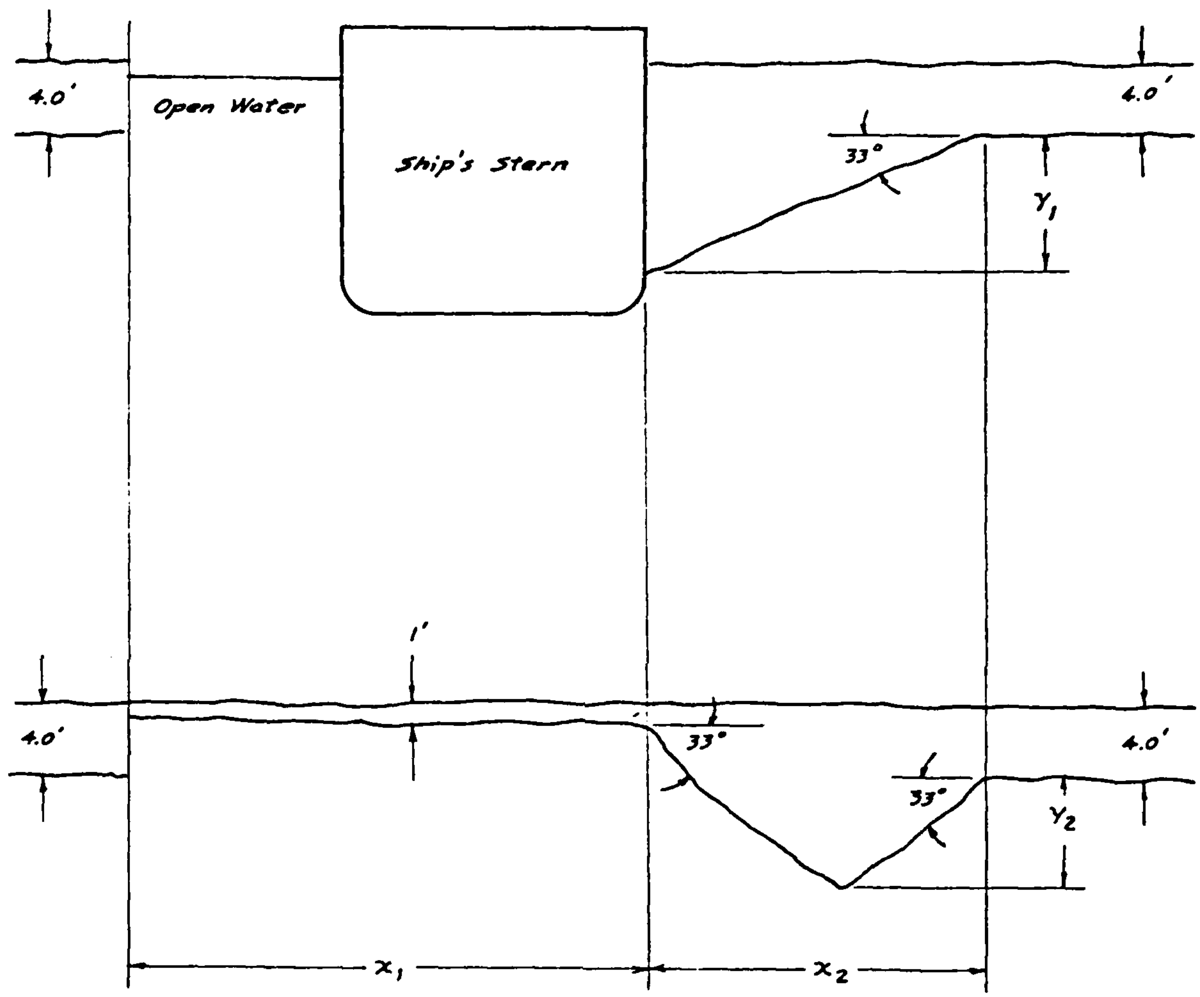


Figure B-12 Assumed Ice Behavior after Ship Passes

$$X_2 = h_B^{1/2} \left(\frac{2\ X_1}{\tan 33°} \right) \tag{B.29}$$

$$Y_1 = X_1 \tan 33° \tag{B.30}$$

$$Y_2 = Y_1/2 \tag{B.31}$$

For the case of a 1000' Laker negotiating Johnsons Point Turn in 4.0' thick uniform brash ice (h_B), β is equal to 1° and the resultant ice distribution in the channel is shown in Figure B-13.

In order to predict vessel behavior in the non-uniform channel, coefficients to the equation of motion were calculated and input to the maneuvering model described in Section B.3 1. It was assumed that the total side force acting on the ship can be expressed as the integral of local side force at any point and that local side force is a function of ice thickness squared and sway velocity. Therefore:

$$Y = A\ v' \cdot \int_{\text{stern}}^{\text{bow}} h^2(x)\ dx \tag{B.32}$$

where

Y = Total side force (lbs)

A = An empirical constant determined from model test results in uniform ice = 315 lbs/ft^3

$h(x)$ = Distribution of ice thickness along the hull (ft)

Similarly, the total yaw moment was assumed to be equal to the integral of side force multiplied by distance from the midbody.

$$N = \int_{\text{stern}}^{\text{bow}} Y(x)\ x\ dx \tag{B.33}$$

where

x = 0 is at the ship midbody

Substitution of Equation (B.32) yields:

$$N = A\ v' \cdot \int_{\text{stern}}^{\text{bow}} h^2(x)\ x\ dx \tag{B.34}$$

First $h(x)$ was determined for specific assumed values of β, based on the ice distribution shown in Figure B.13. Next, Y and N were calculated from Equations (B.33) and (B.34) and Y'_v, N'_v, Y'_r, and N'_r were estimated. These values were then input to the maneuvering model and β, R, δ and transit time were calculated. This process was repeated until the calculated value of β was equal to the assumed value.

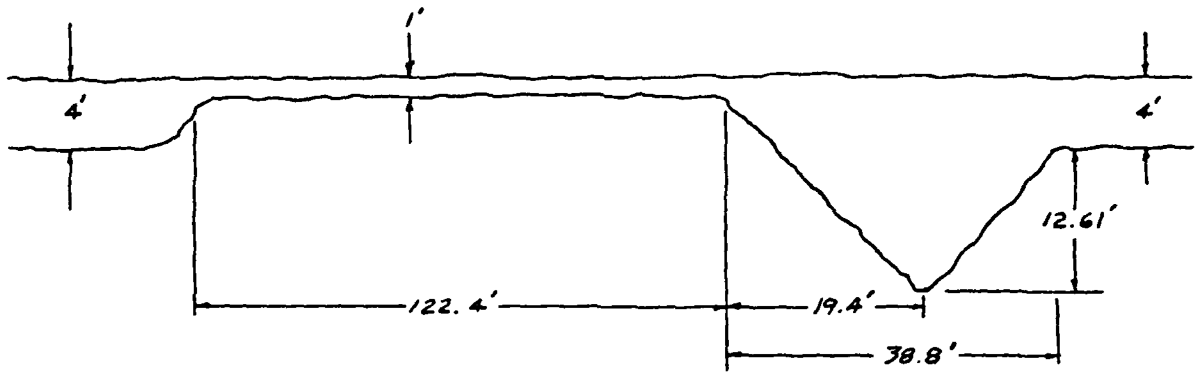


Figure B-13 Ice Distribution Across Channel After Passage of 1000' Laker Through Johnsons Pt. Turn

Table B.1 compares the behavior of the 1000' ship in the irregular channel to the behavior in uniform 4.0' thick brash. As illustrated in the table, the ice buildup at the outside of the turn increases transit time from 20.3 to 35.3 minutes with one additional back-and-fill cycle required. It should be noted, however, that the angle of attack is greater than for the uniform ice case and the build-up of ice will therefore be moved further out from the inside of the turn. For this reason, it is felt that ice build-up is not a significant consideration since subsequent ship passages will maintain the position of the berm at the extreme outside edge of the channel and conditions will, therefore, not be as severe as those investigated above. For smaller ships the ice buildup should be less of a problem since they require less channel width to negotiate the turns than do the 1000' ships.

TABLE B.1 EFFECTS OF ICE BUILDUP ON THE BEHAVIOR OF 1000' LAKER AT JOHNSON'S POINT TURN

	BEHAVIOR IN CHANNEL SHOWN IN FIGURE	BEHAVIOR IN 4.0' UNIFORM BRASH
β	2.6°	1.1°
$R_{minimum}$	3834 ft	2583 ft
No. of Back and Fills	2	1
V_{avg}	0.9 MPH	1.1 MPH
Transit Time	35.3 min.	20.3 min.

B.4 Transit Times and Calculation of Delays

Delay time is the major variable being measured by the model. Brash ice thickness is predicted for a given time period by the methodology developed in Section B.1 the vessel speed is caluclated as shown in Section B.2, and then the delay experienced in the straightaways is calculated by the following equation:

$$\text{Delay}_{SA} = \frac{\text{Reach}}{V_{BI}} - \frac{\text{Reach}}{V_{OW}} \tag{B.35}$$

where:

Delay_{SA} = The increased transit time in hours over open water transit time for straightaways.

Reach = The length of the river in miles

V_{BI} = The average speed of the vessel in brash ice in MPH

V_{OW} = The average open water speed.

The total delay is then:

$$\text{Total Delay} = \text{Delay}_{SA} + \text{Delay}_{IT} \tag{B.36}$$

where:

Delay_{IT} = The delay in the turns

Delay in the turns is determined from Figure B-8.

When the ships get stuck the delay is set to 24 hours for each day traffic cannot move plus the delay for the day when traffic first can move. The point at which ships stick is determined by comparing the ice thickness to the thickness where the ships stick in the turns for each vessel type or when the average speed reaches 2 MPH.

B.5 Removal Rates

Initially, removal rates required to maintain traffic were determined by running the model, limiting the ice thickness to a point just less than that where the vessel sticks and calculating the growth rate of ice at that thickness. A removal rate equal to the growth rate would be required to maintain traffic, therefore, the model was subsequently modified to input fixed removal rates using a variety of removal strategies. This allowed a more realistic and flexible appraisal of the required rates. The manner in which removal rates were handled will be dicussed with the presentation of results for each removal rate study in the following appendices.

APPENDIX C

ICE GROWTH AND STRAIGHTAWAY TRANSIT TIME STUDY

APPENDIX C

ICE GROWTH AND STRAIGHTAWAY TRANSIT TIME STUDY

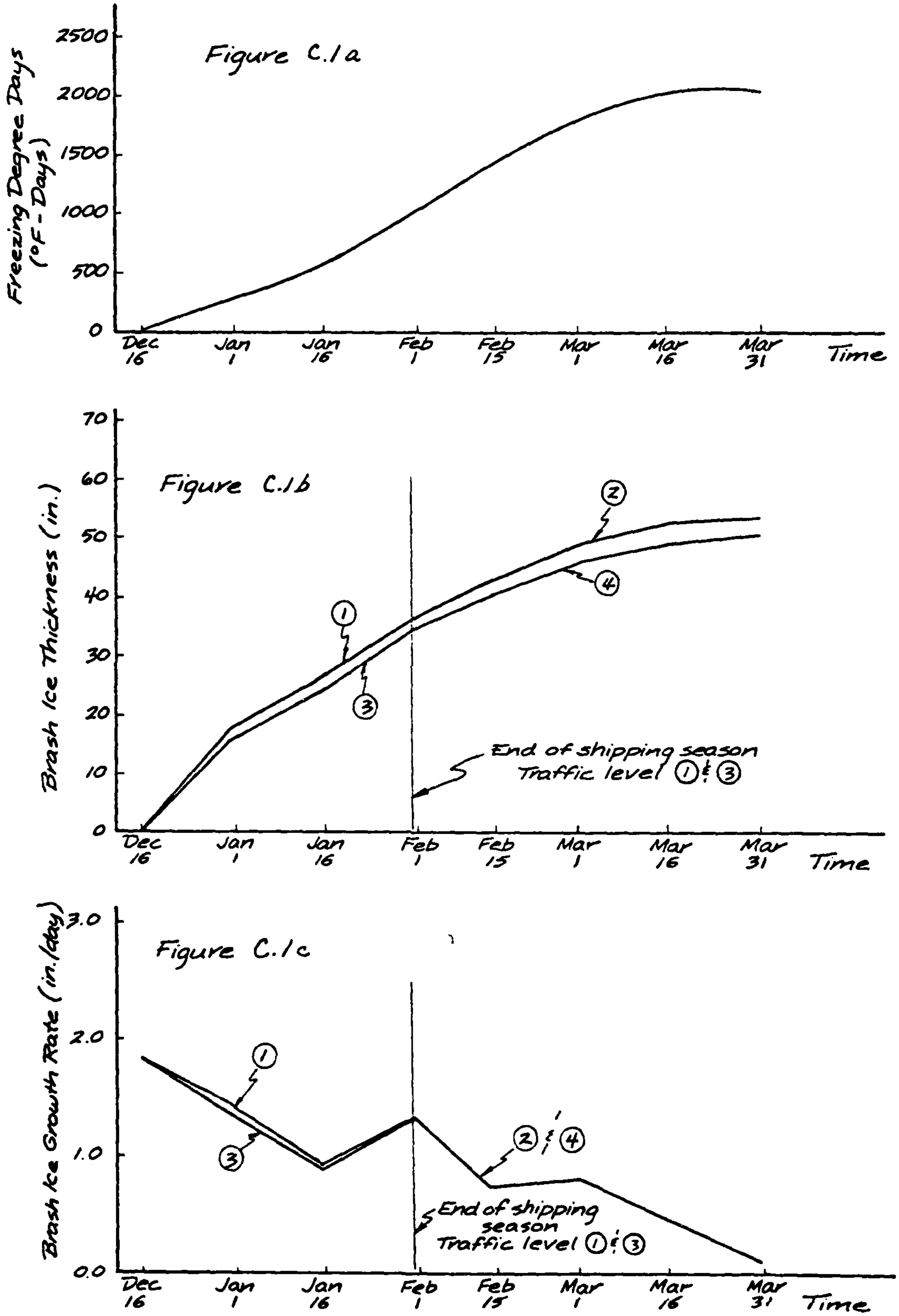
The mathematical model was exercised for a 1000 ft Laker in the St. Marys River and a 730 ft Laker in the St. Lawrence Seaway for the five winters of different severity. Figures C.1 through C.10 show the cumulative freezing degree days, brash ice thickness, brash ice growth rate, ship speed, and relative time of transit compared to open water versus time for the St. Marys and St. Lawrence Rivers for the five winters. No delay in turns was calculated for this study.

On the St. Marys River the maximum predicted brash ice thickness occurs at the end of the severe winter. From Figure C.1b, the maximum ice thickness is 52.5 inches. The corresponding slowest vessel speed in the straightaways is shown in Figure C.1d to be 4.4 miles per hour. At this speed it takes about 11 hours to transit the river from the Soo Locks to Detour Passage. This represents a delay of approximately 7 hours over the open water transit time. Therefore, it would seem that the ships will operate with acceptable delay times, provided they are able to negotiate the turns.

On the St. Lawrence River, the brash ice may grow to a thickness greater than the ships are able to traverse a straight line. Figures C.6d, C.7d, and C.8d all indicate that some time before the end of the shipping season the vessels will become stuck in the brash ice. For the severe winter, the vessels will become stuck in early February. For the colder and the average winter, the vessels will become stuck in late February. It is apparent from the figures that relative transit times many times greater than the open water time can occur on the St. Lawrence River.

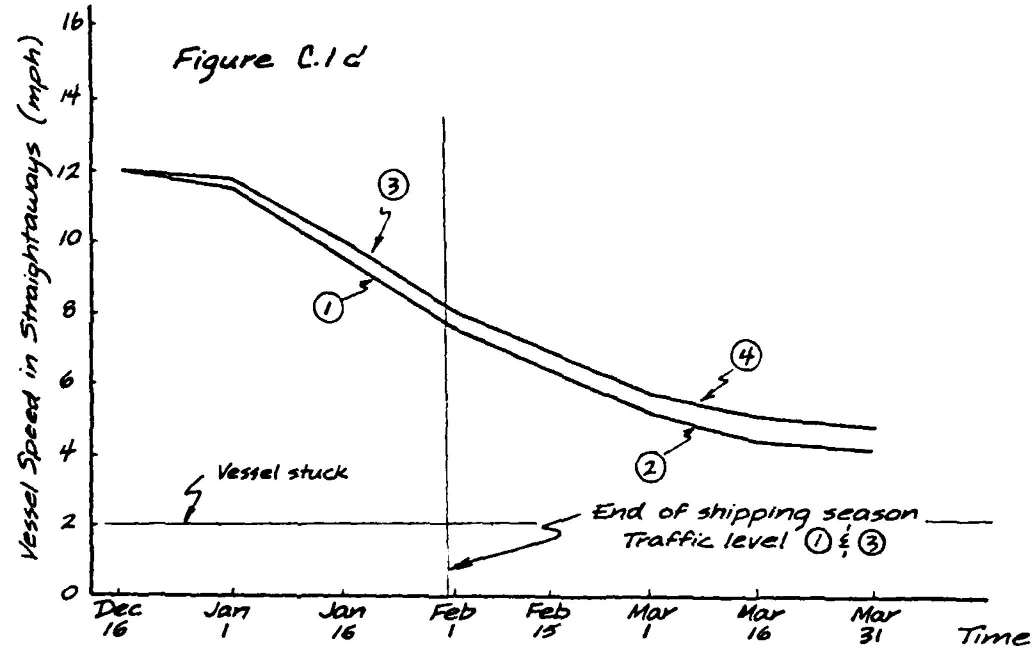
In viewing the data, one should note that the ice gets thicker much faster on the St. Lawrence River than on the St. Marys River. Very cold weather seems to come earlier on the St. Lawrence River, but the main reason for increased ice thickness is a higher growth factor. This fact, as well as the much longer length of the river, permit very long delays to occur (9 hour delay is a relative transit time of 2.25 over an open water transit on the St. Marys River, but only a relative transit time of 1.20 on the St. Lawrence River).

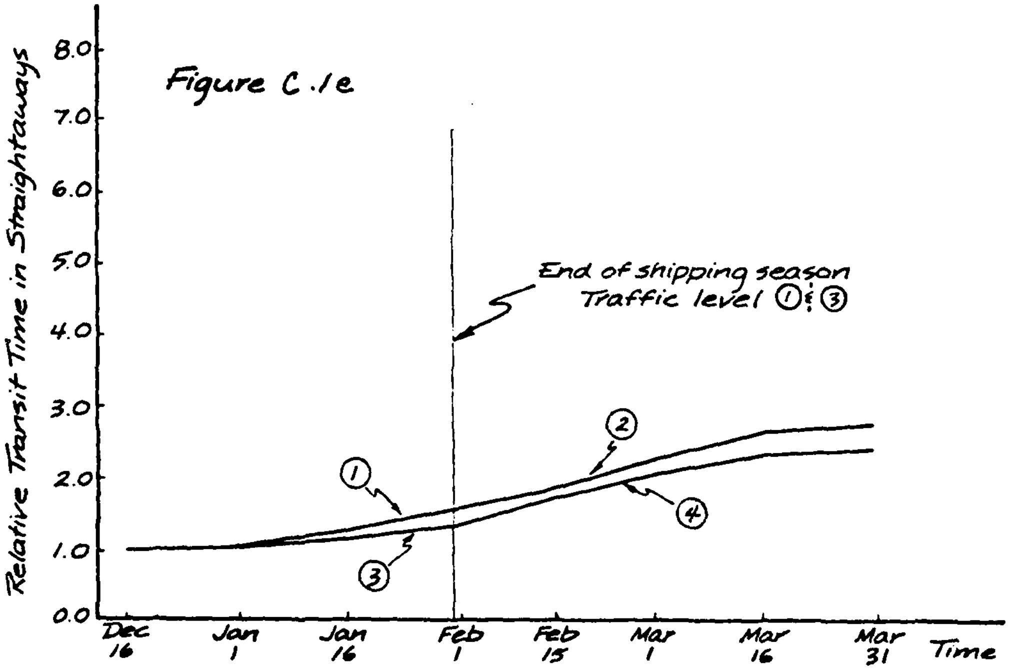
Figure C.1 St. Marys River — Severe Winter — 1969-1970



Note: Circled numbers indicate traffic level.

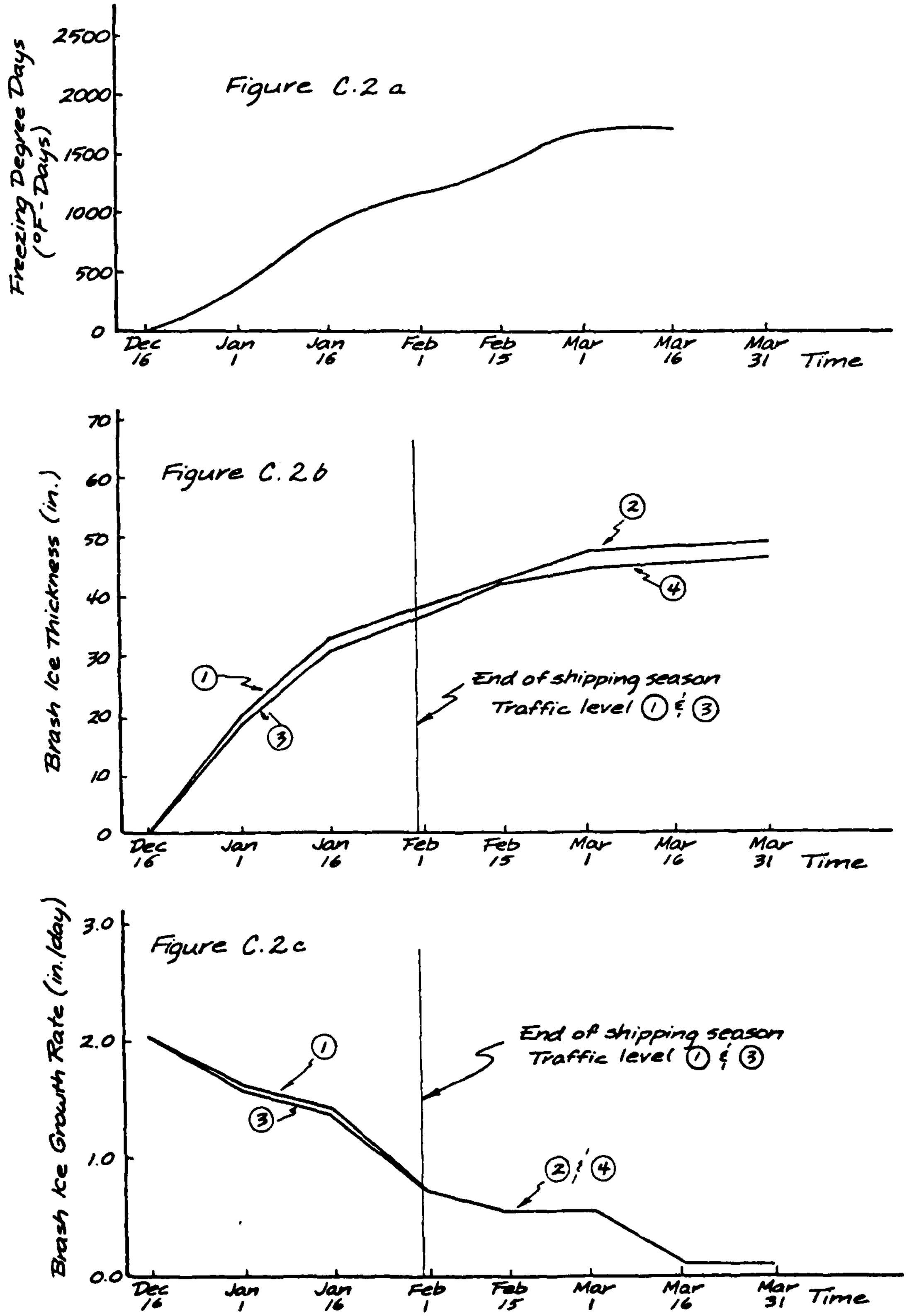
Figure C.1 St. Marys River — Severe Winter — 1969-1970





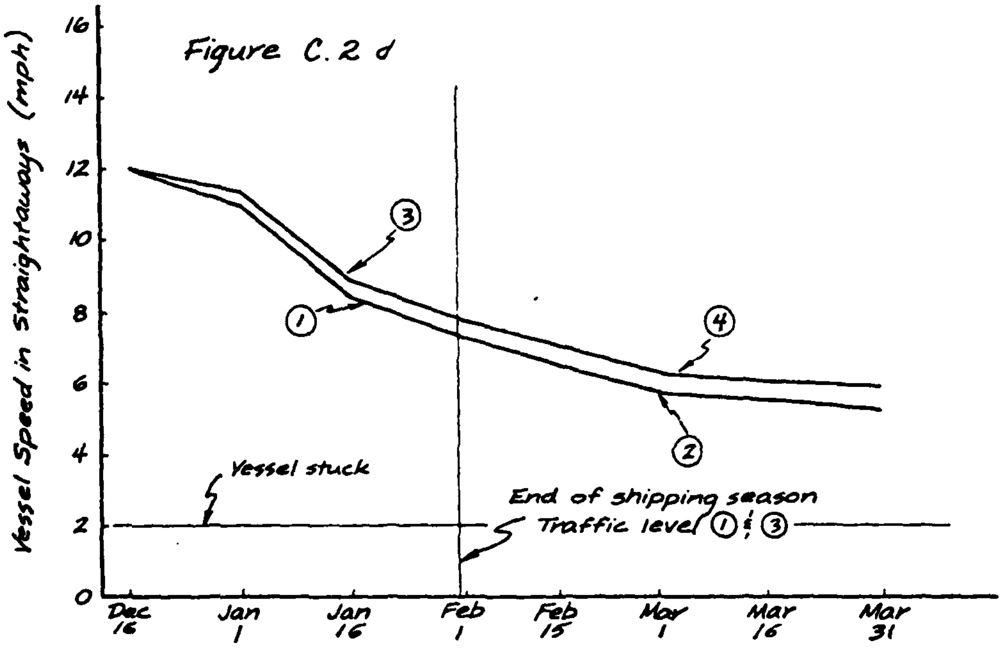
Note: Circled numbers indicate traffic level.

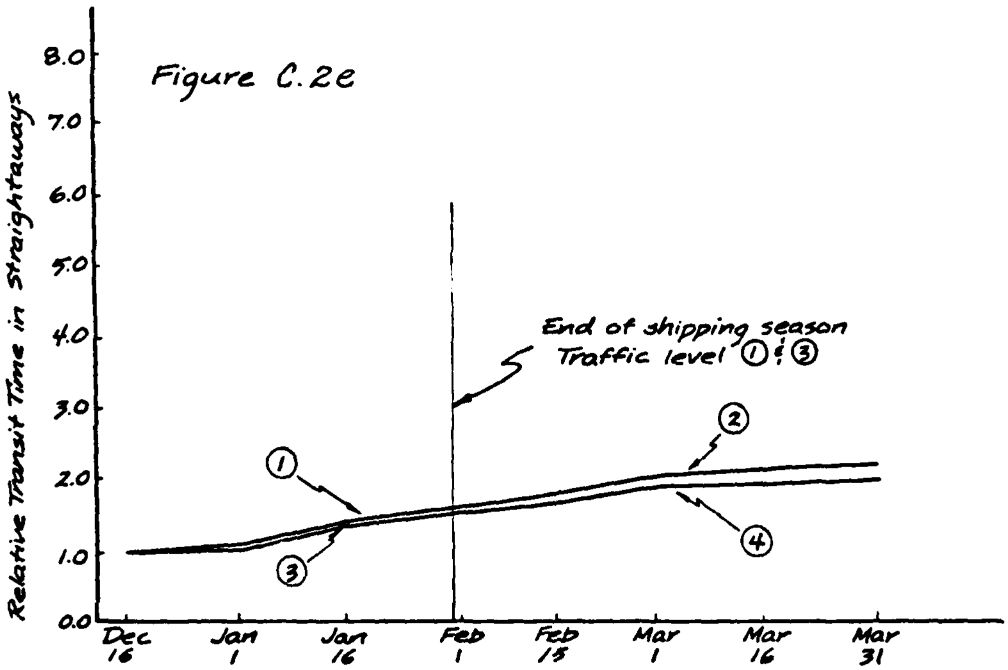
Figure C.2 St. Marys River — Colder Winter — 1976-1977



Note: Circled numbers indicate traffic level.

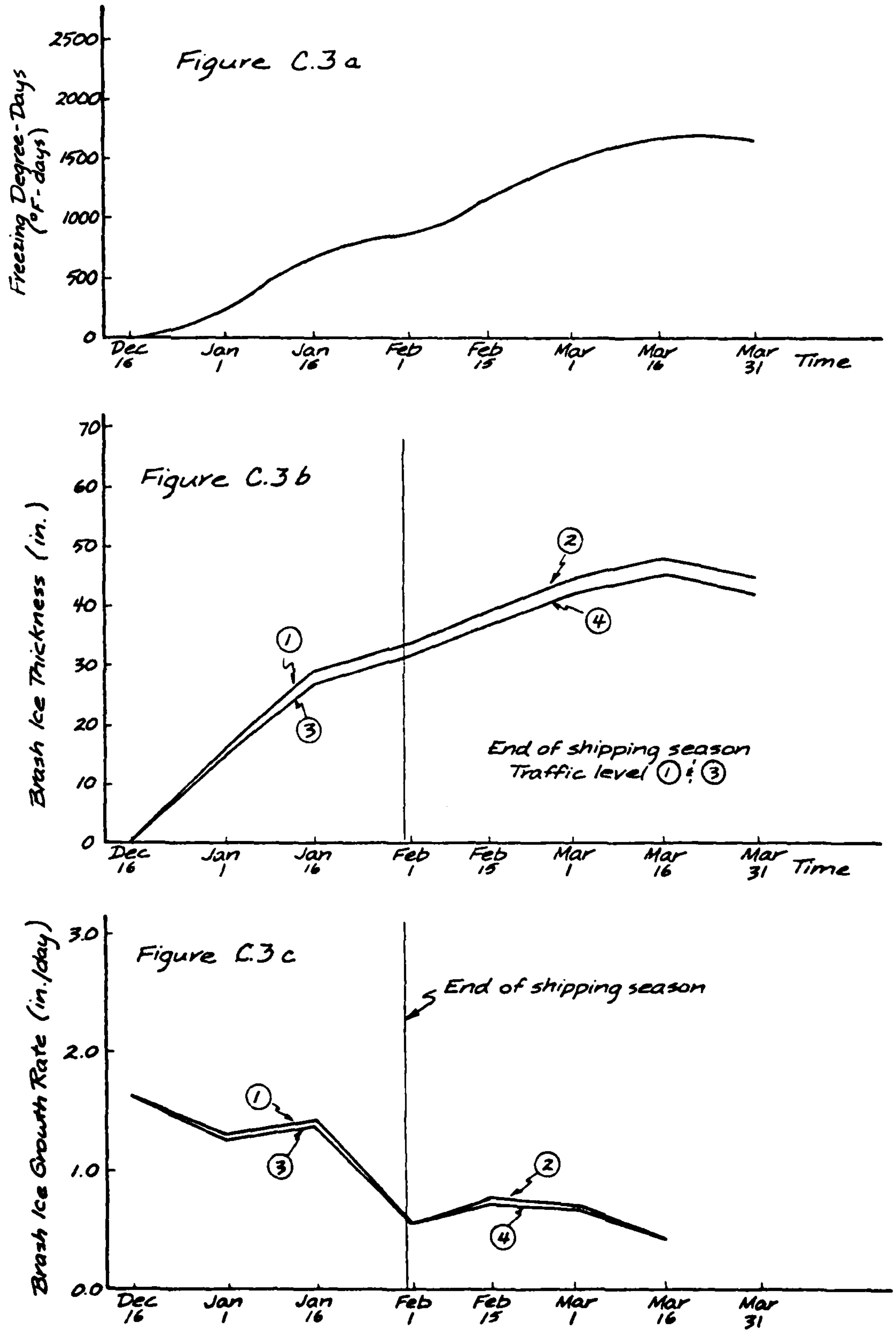
Figure C.2 St. Marys River — Colder Winter — 1976-1977





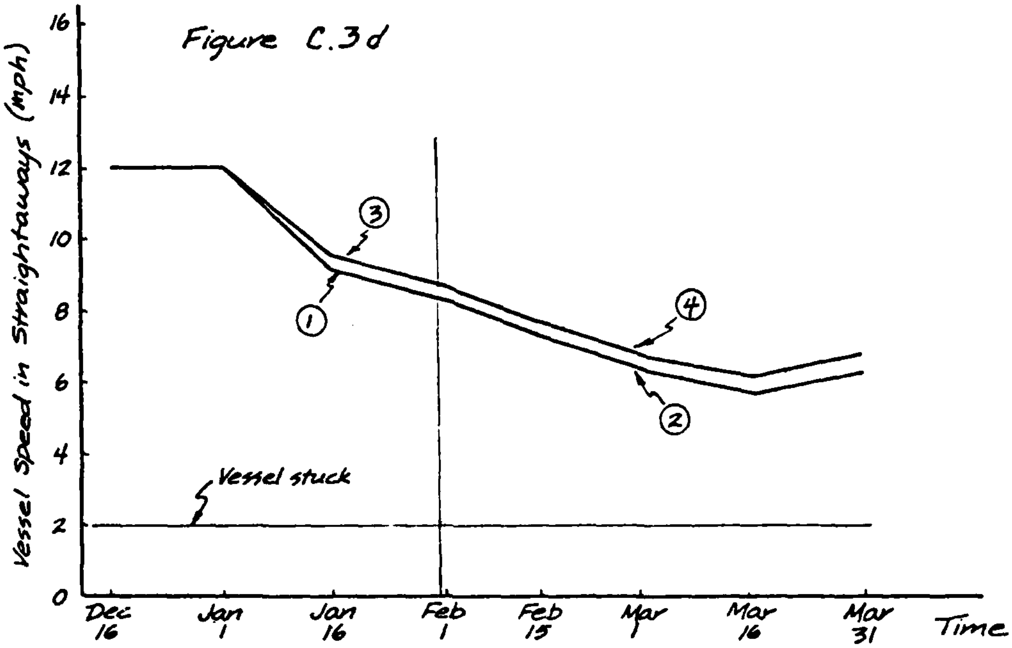
Note: Circled numbers indicate traffic level.

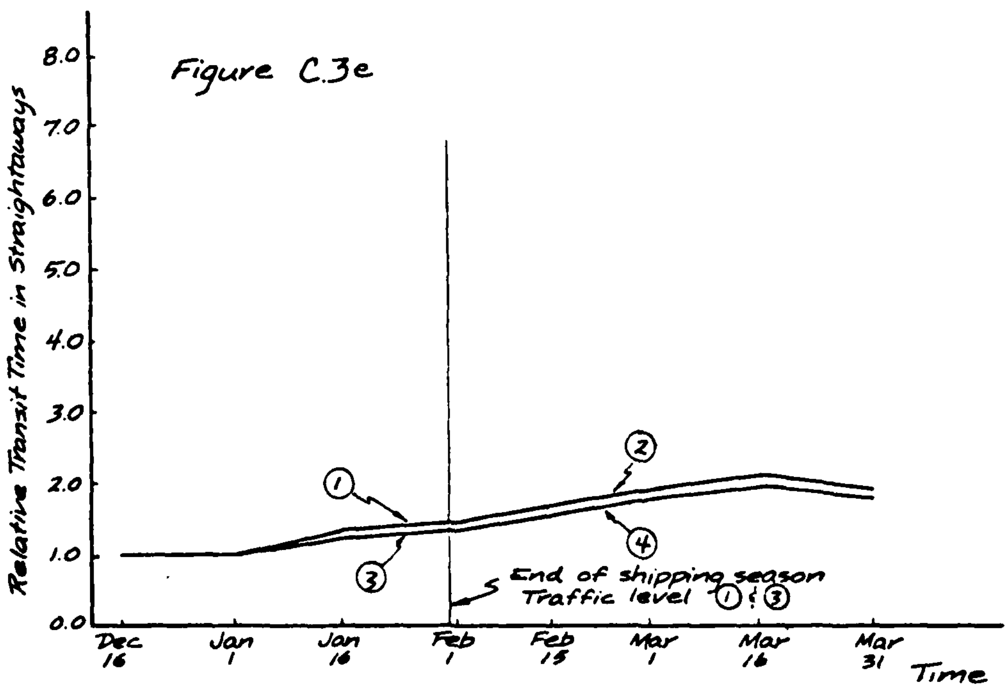
Figure C.3 St. Marys River — Average Winter — 1968-1969



Note : Circled numbers indicate traffic level.

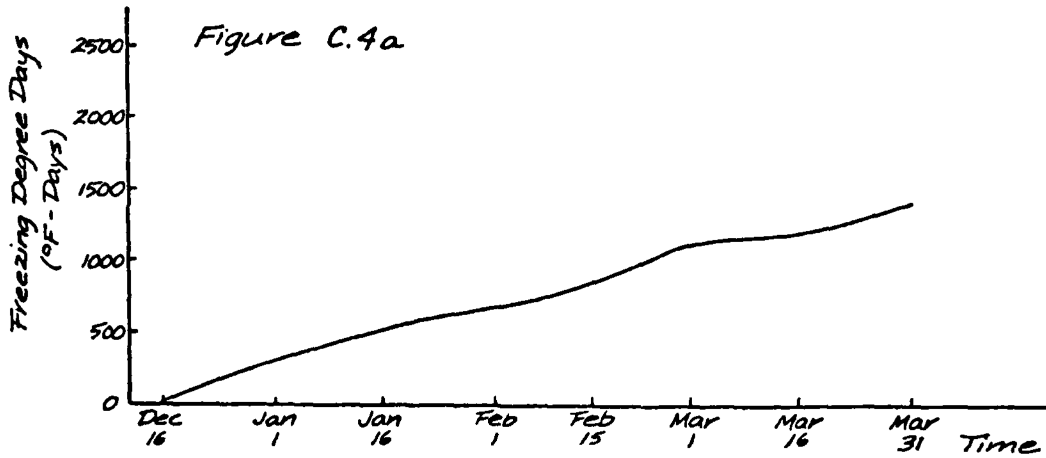
Figure C.3 St. Marys River — Average Winter — 1968-1969

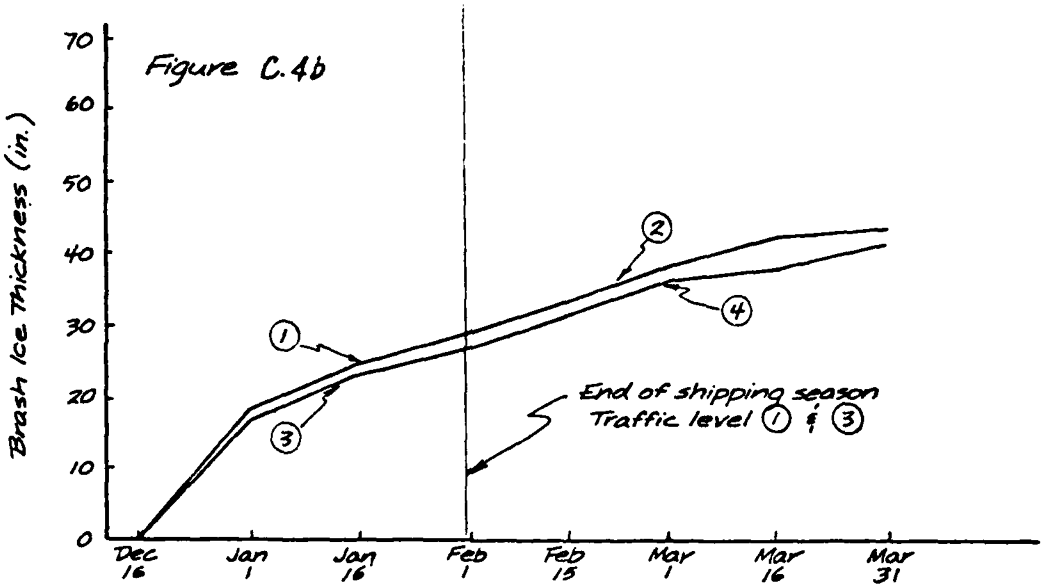


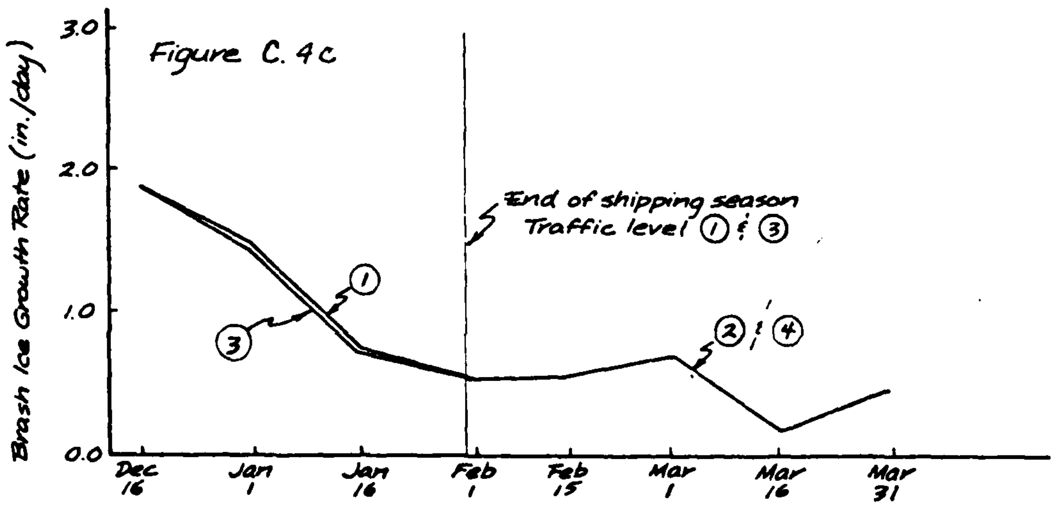


Note: Circled numbers indicate traffic level.

Figure C.4. St. Marys River — Milder Winter — 1965-1966

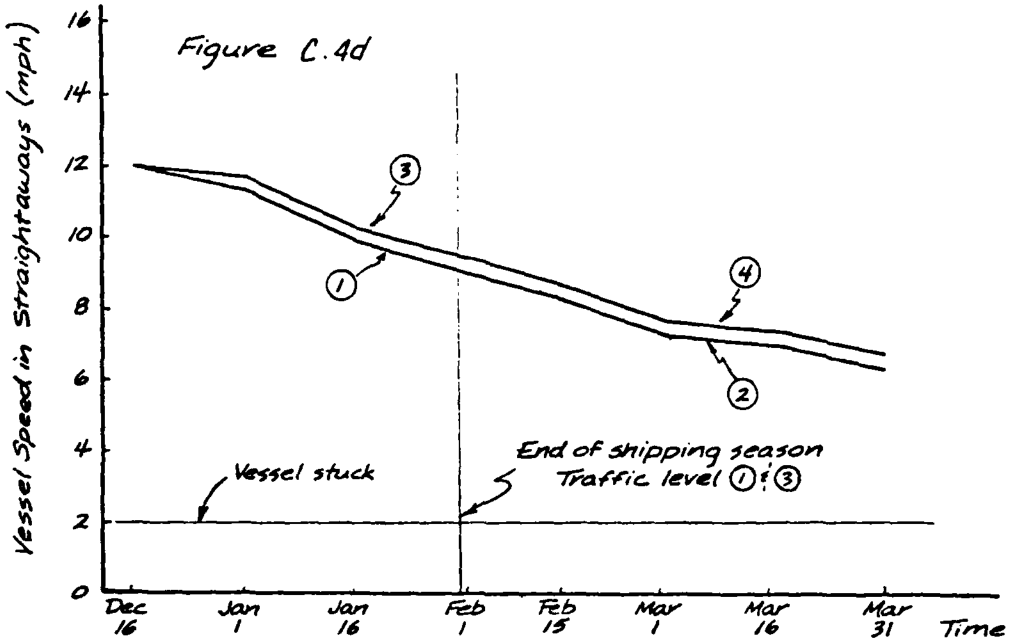


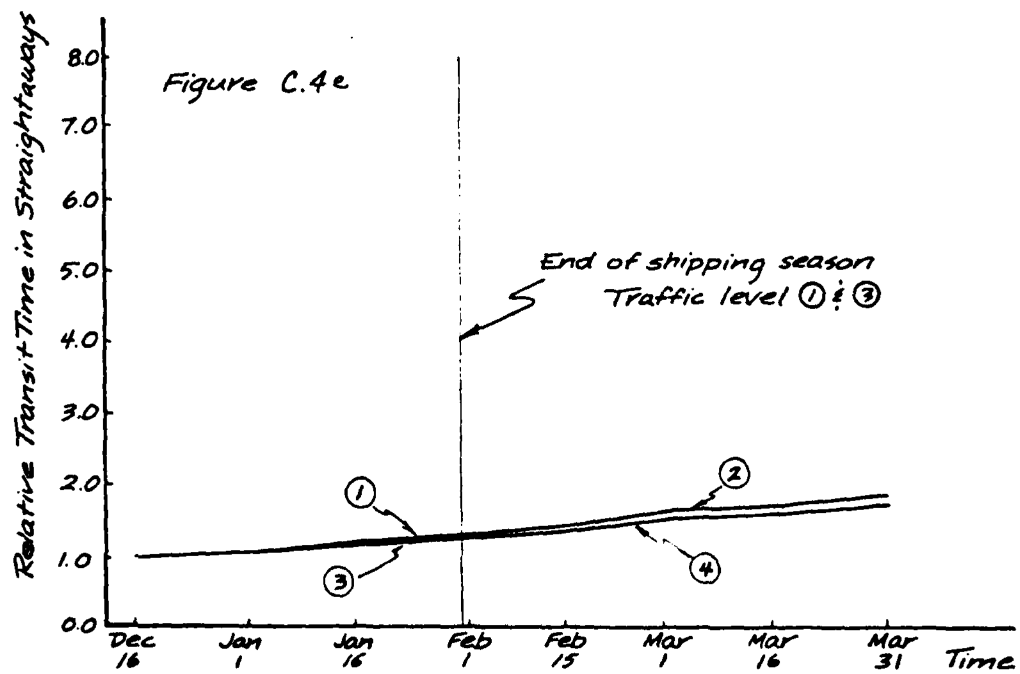




Note: Circled numbers indicate traffic level.

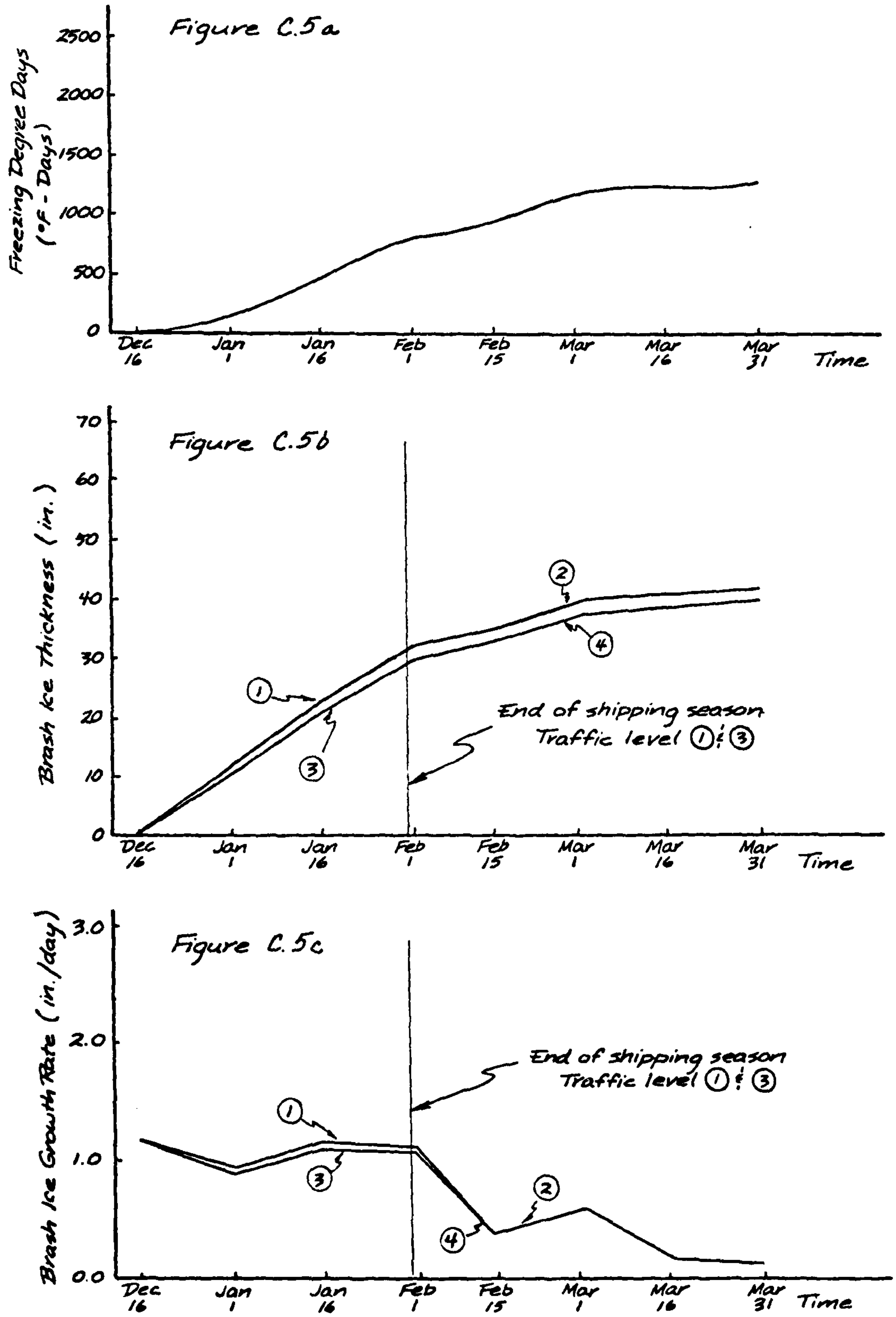
Figure C.4. St. Marys River — Milder Winter — 1965-1966





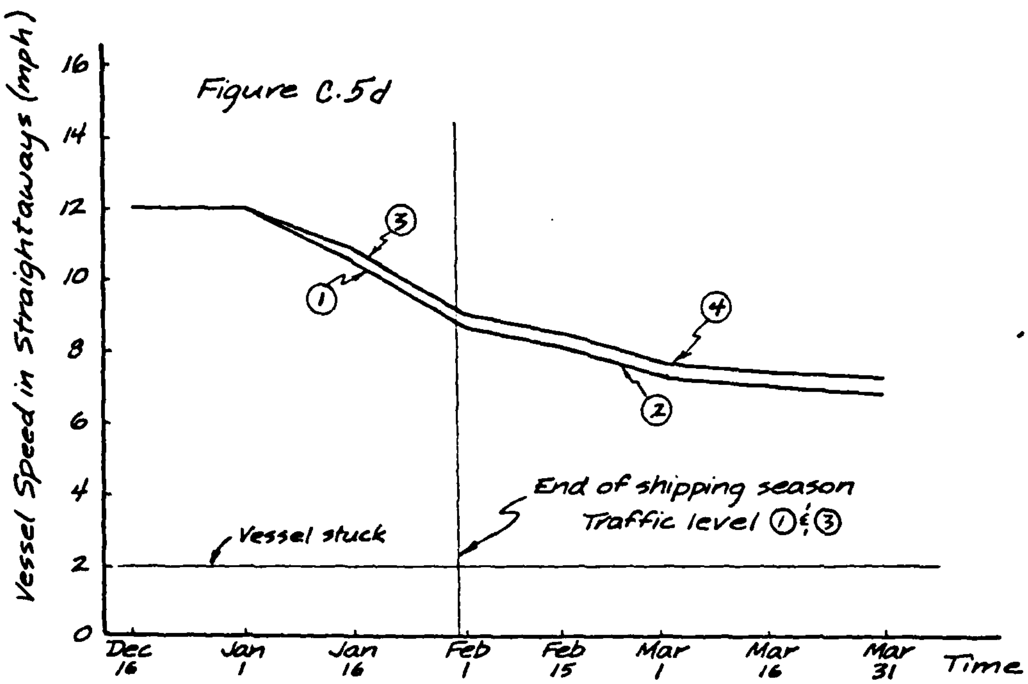
Note : Circled numbers indicate traffic level.

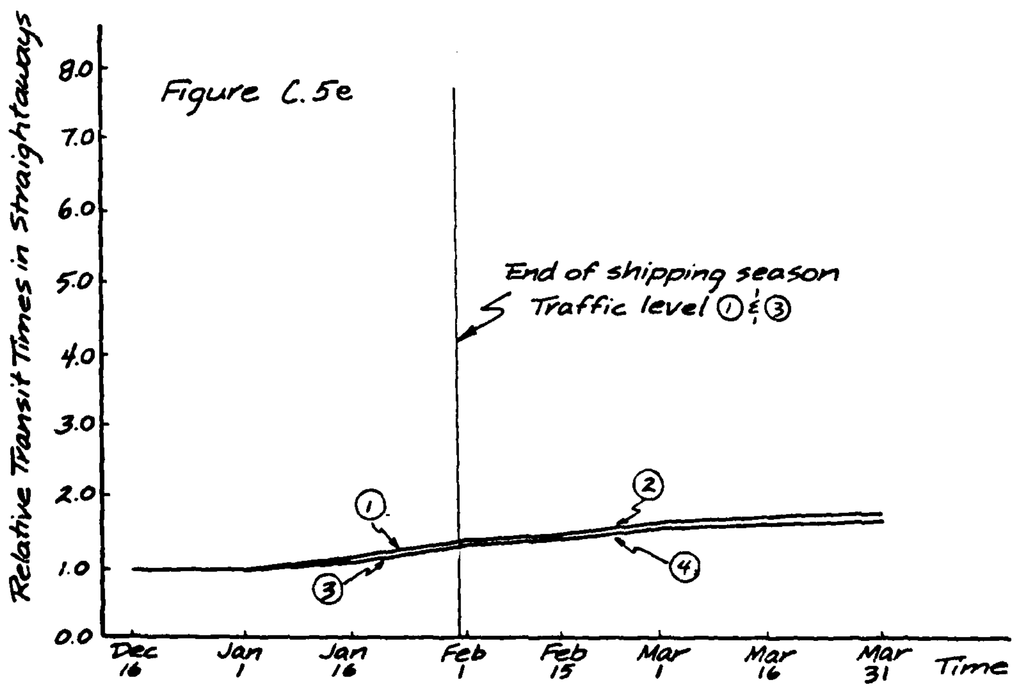
Figure C.5. St. Marys River — Mild Winter — 1952-1953



Note: Circled numbers indicate traffic level.

Figure C.5 St. Marys River — Mild Winter — 1952-1953





Note: Circled numbers indicate traffic level.

Figure C.6 St. Lawrence Seaway - Severe Winter - 1969-1970

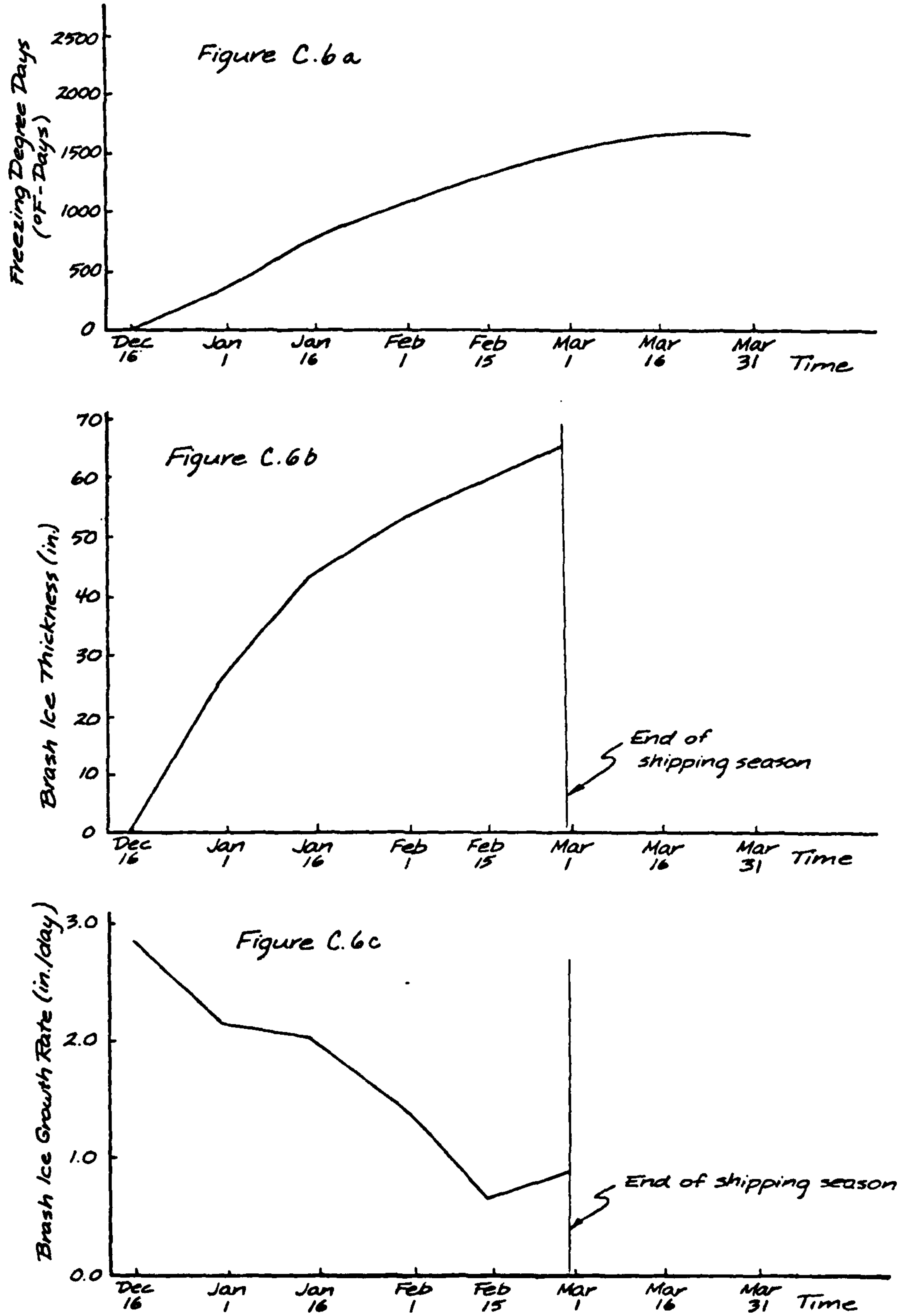
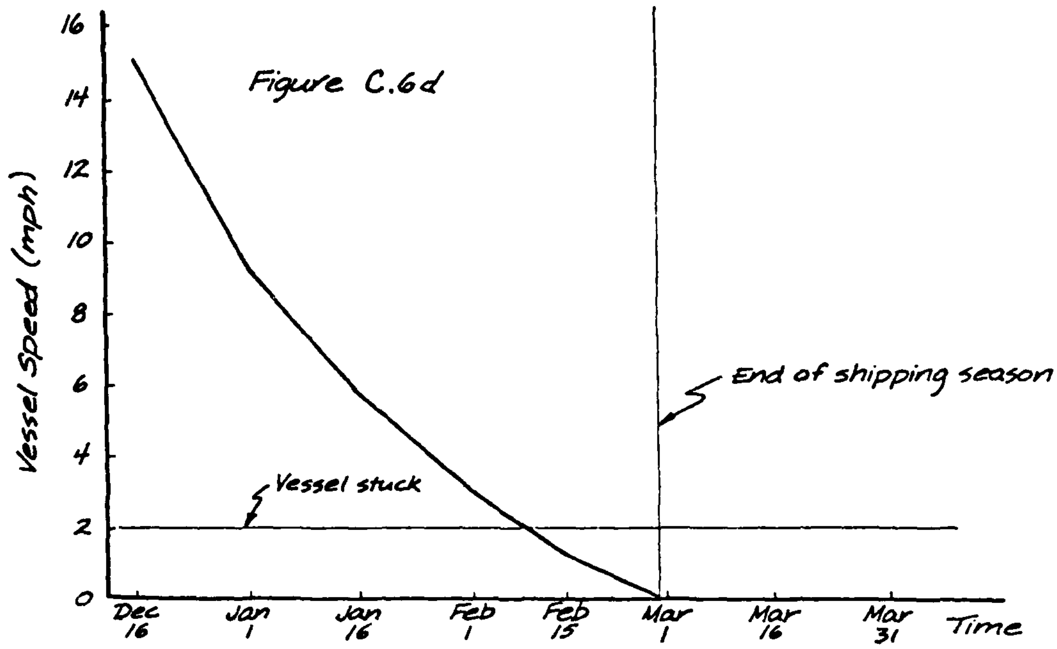


Figure C.6 St. Lawrence Seaway — Severe Winter — 1969-1970



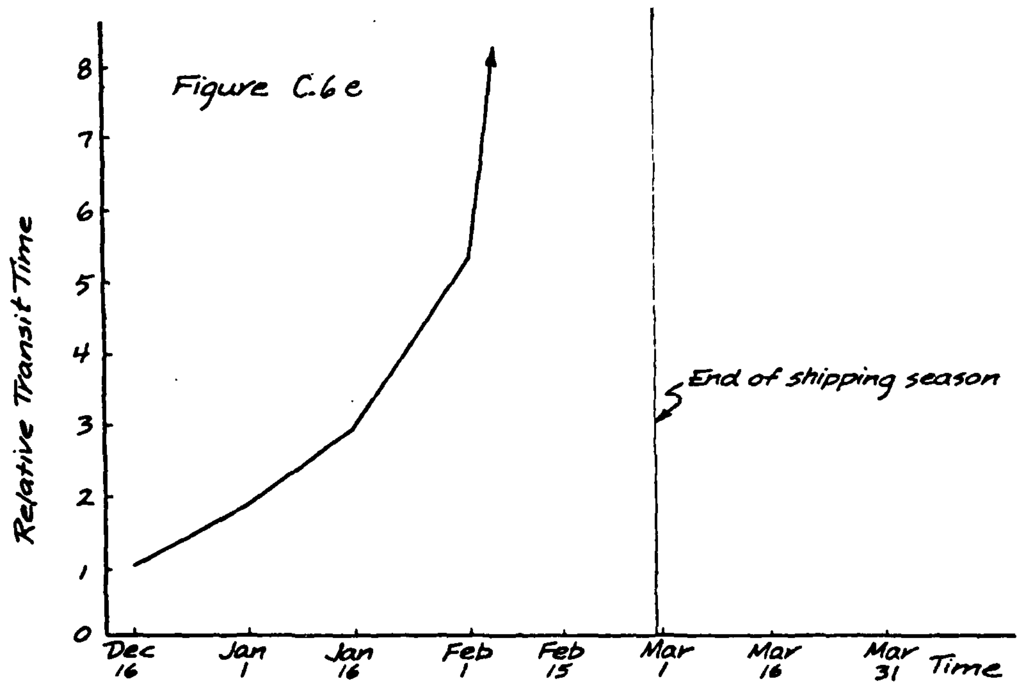


Figure C.7 St. Lawrence Seaway — Colder Winter — 1967-1968

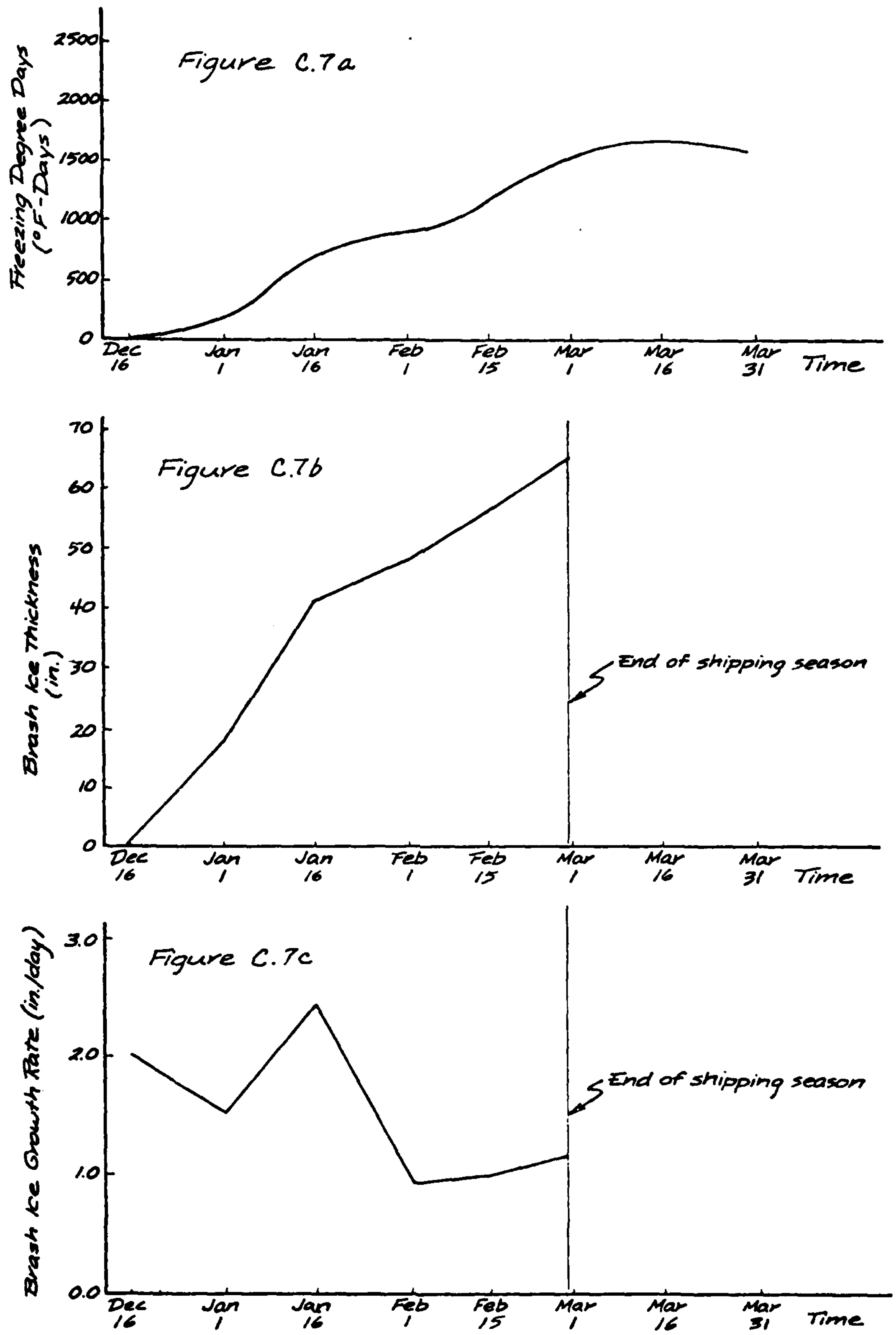
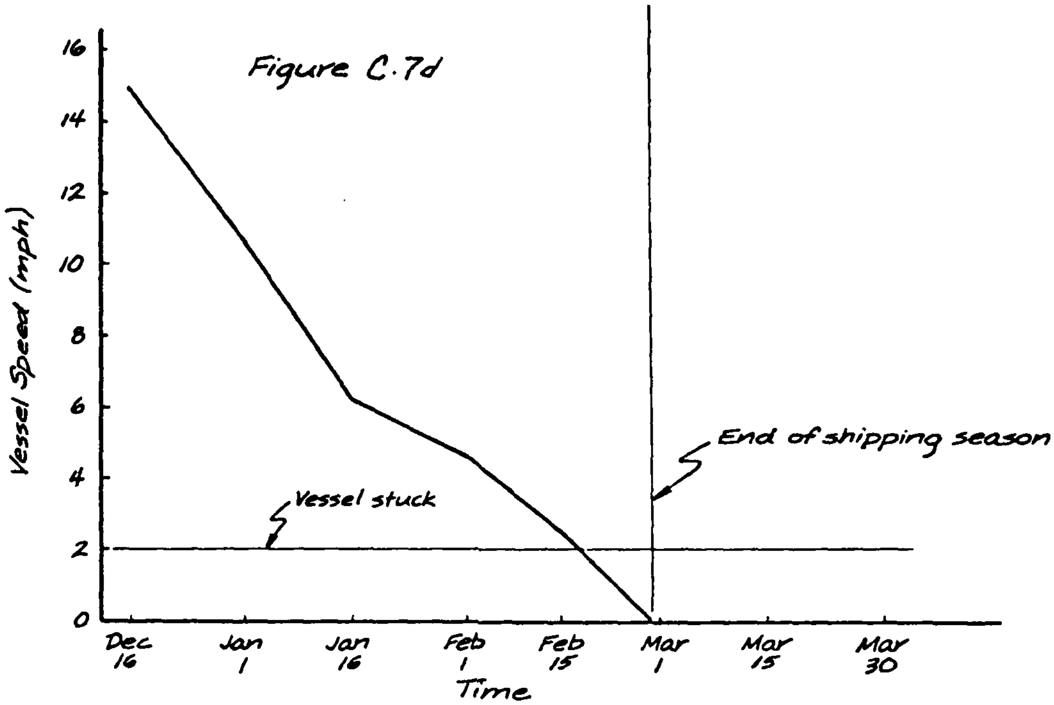


Figure C.7 St. Lawrence Seaway—Colder Winter—1967-1968



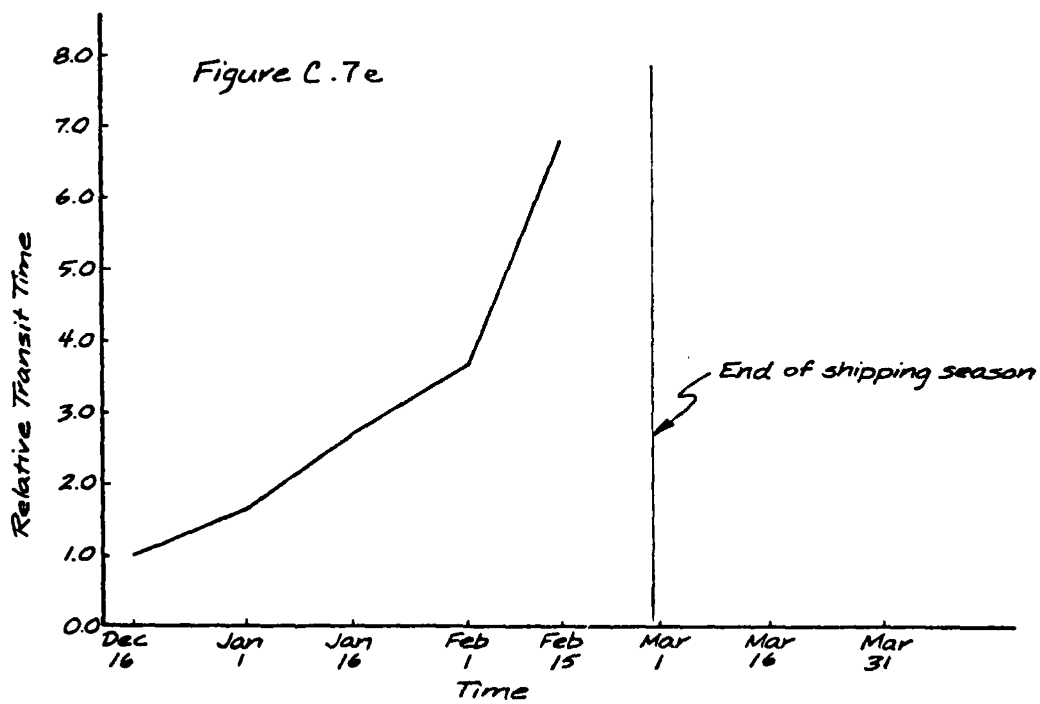


Figure C.8. St. Lawrence Seaway—Average Winter—1968–1969

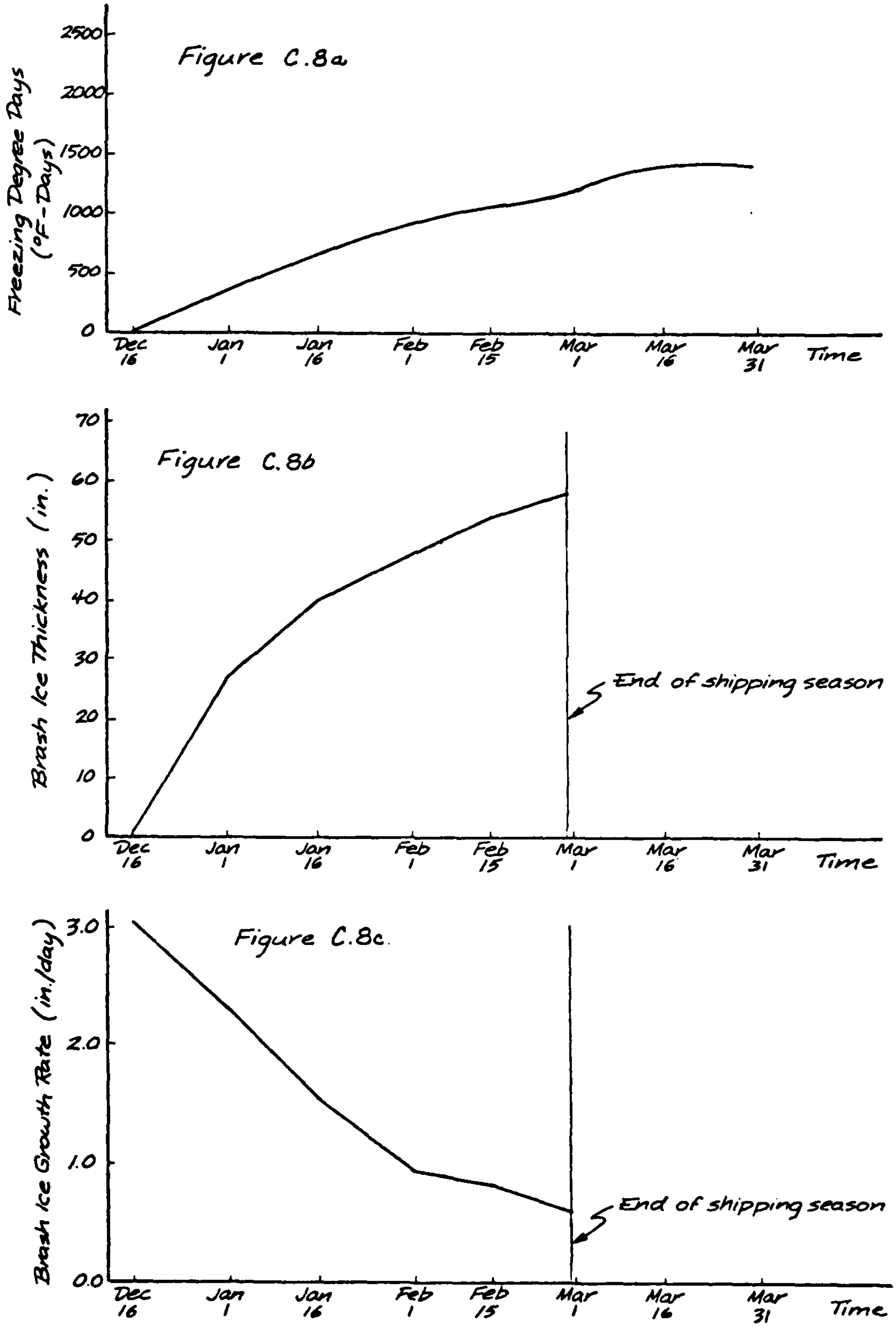
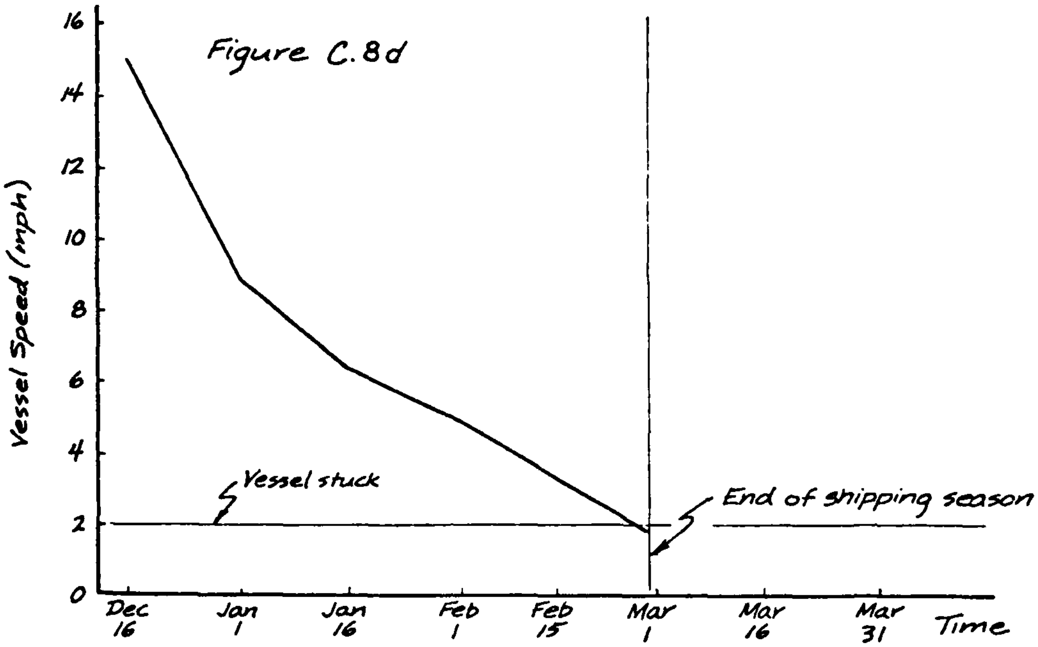


Figure C.8 St. Lawrence Seaway — Average Winter — 1968-1969



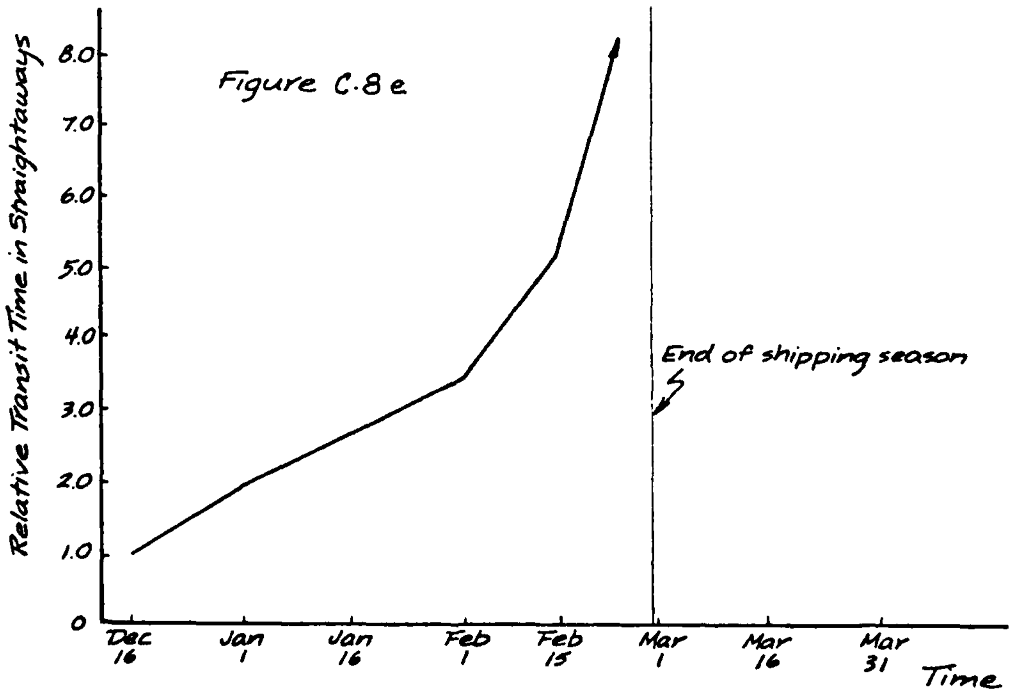


Figure C.9 St. Lawrence Seaway — Milder Winter — 1965-1966

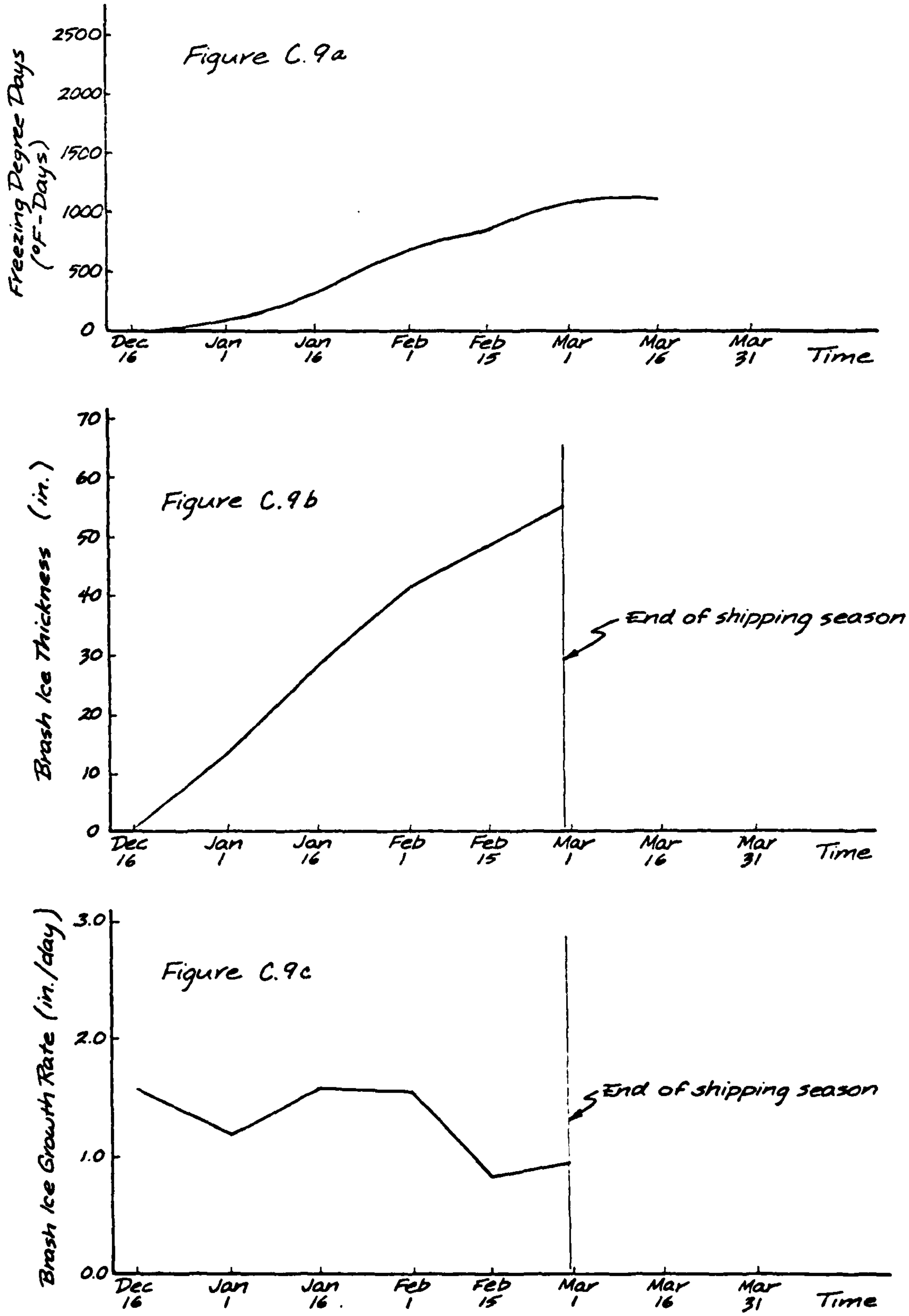
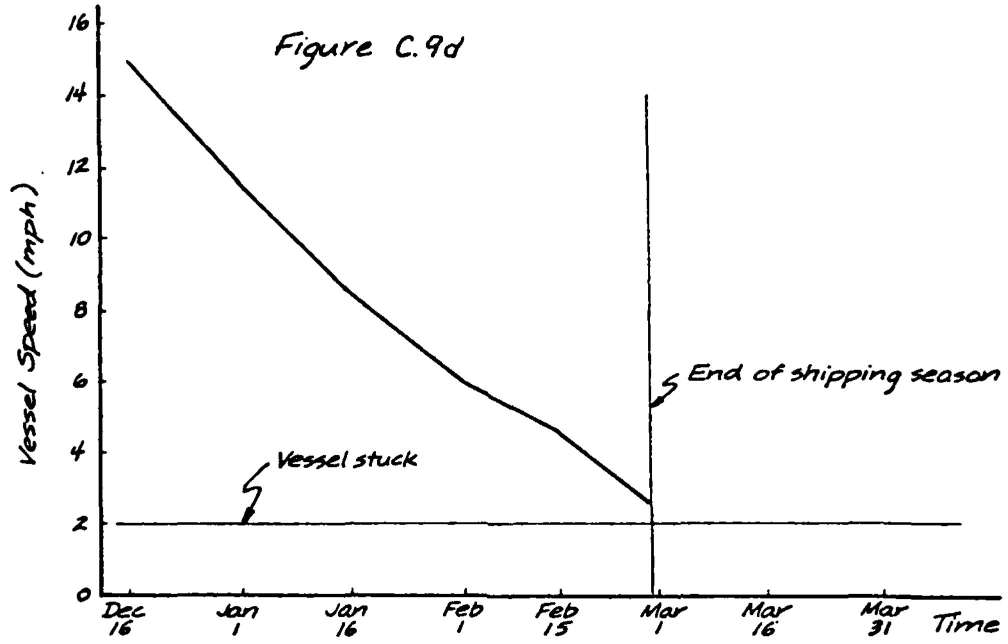


Figure C.9 St. Lawrence Seaway – Milder Winter – 1965-1966



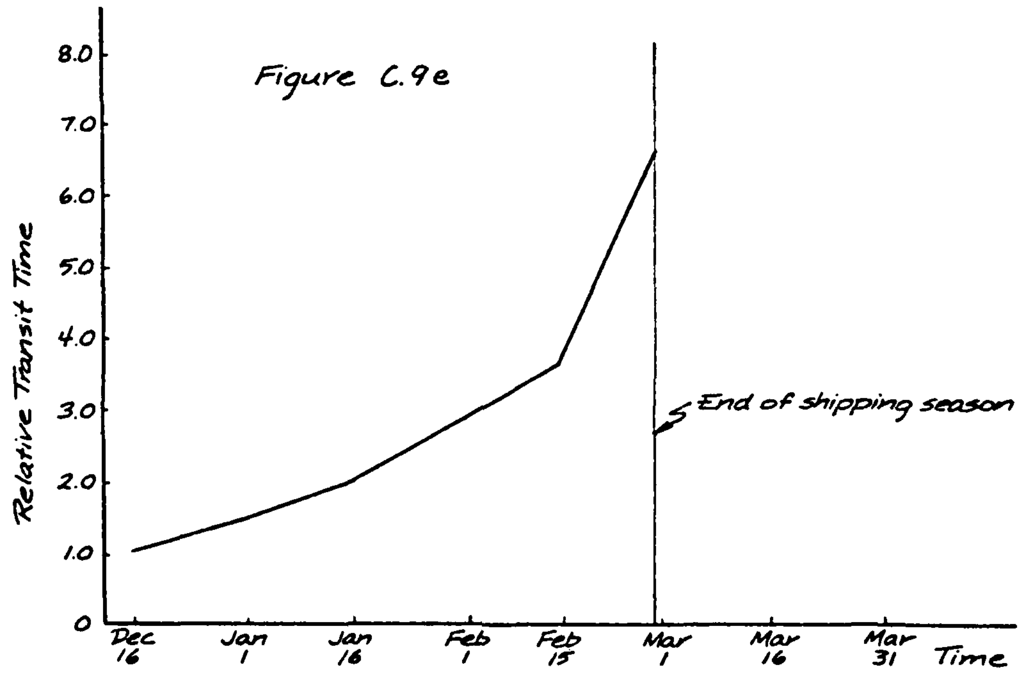


Figure C.10 St. Lawrence Seaway – Mild Winter – 1952-1953

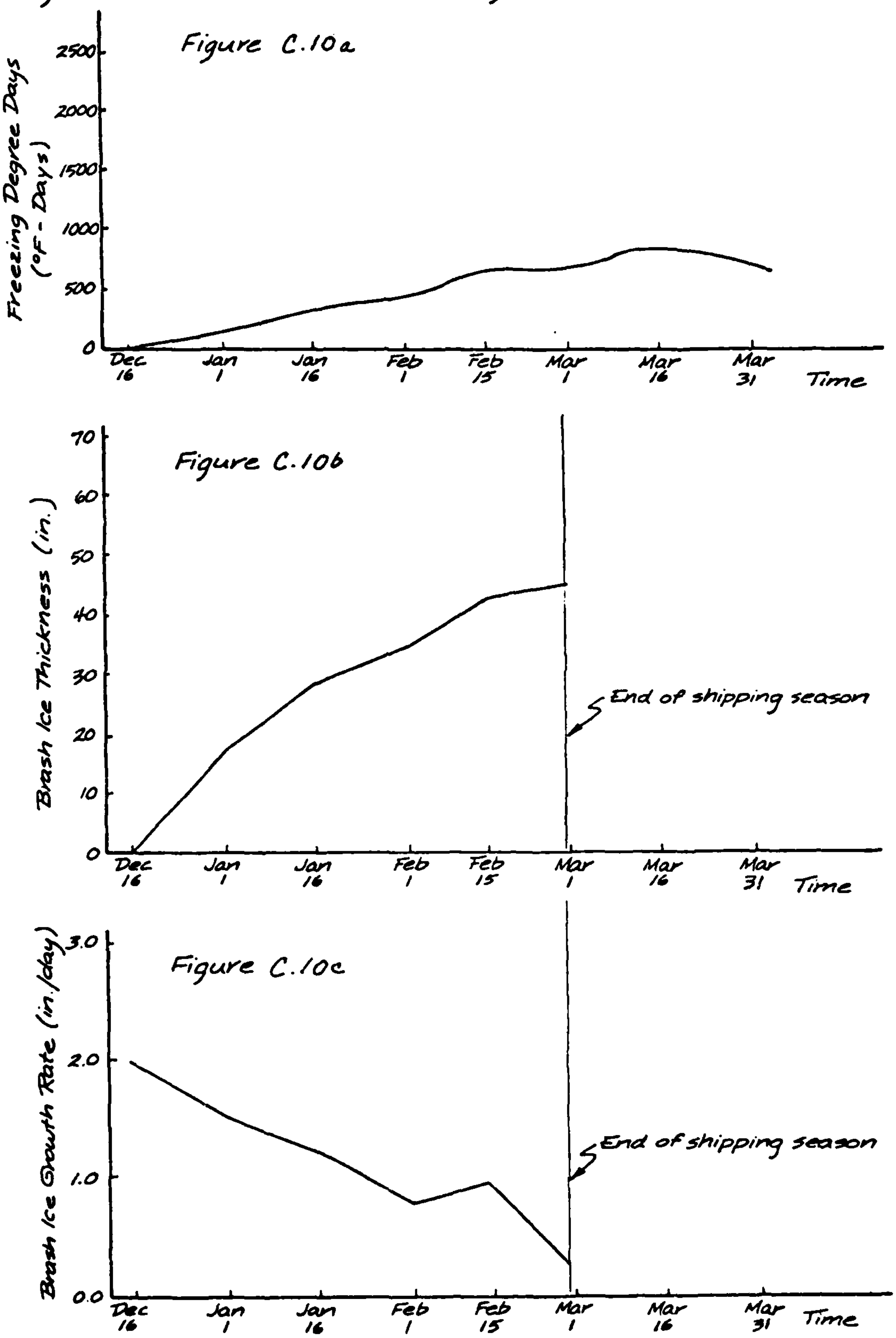
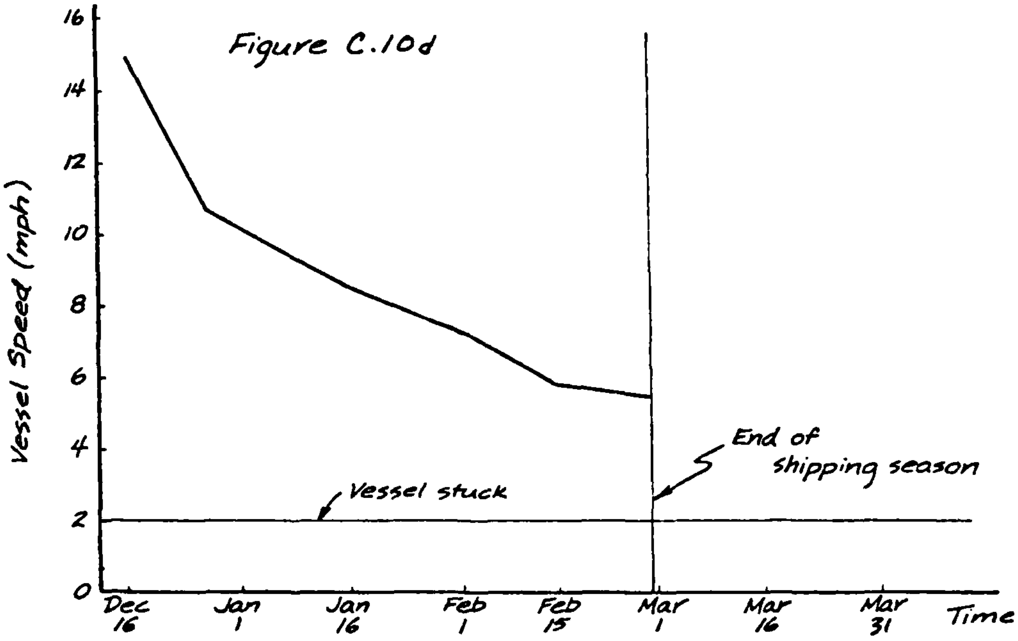
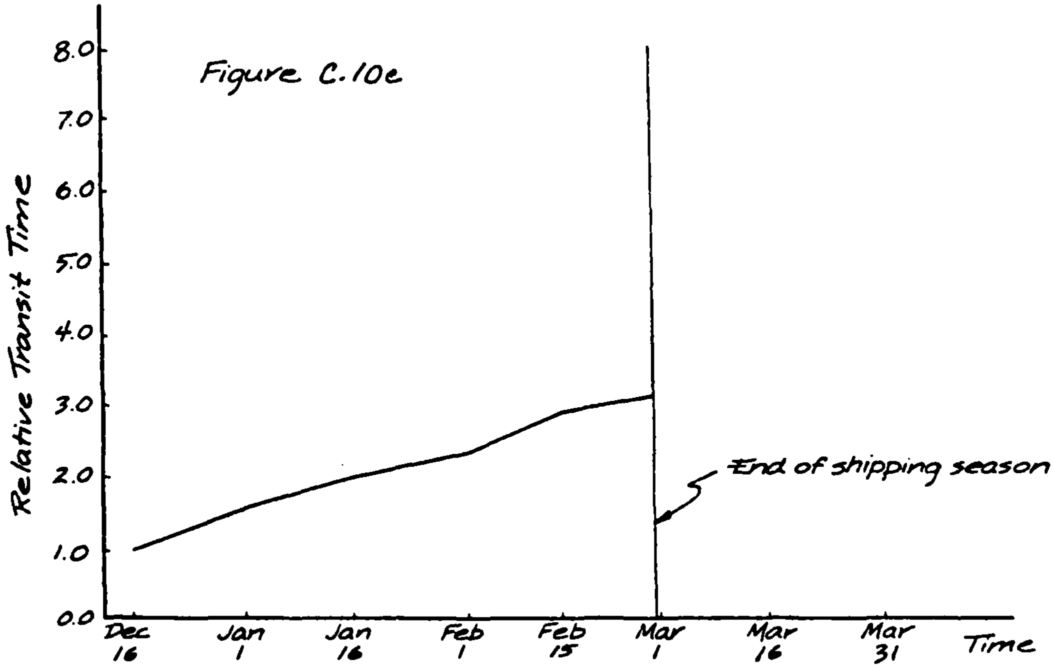


Figure C.10 St. Lawrence Seaway – Mild Winter – 1952-1953





APPENDIX D

TRANSIT TIME VALIDATION/COMPARISON STUDY IN THE ST. MARYS RIVER

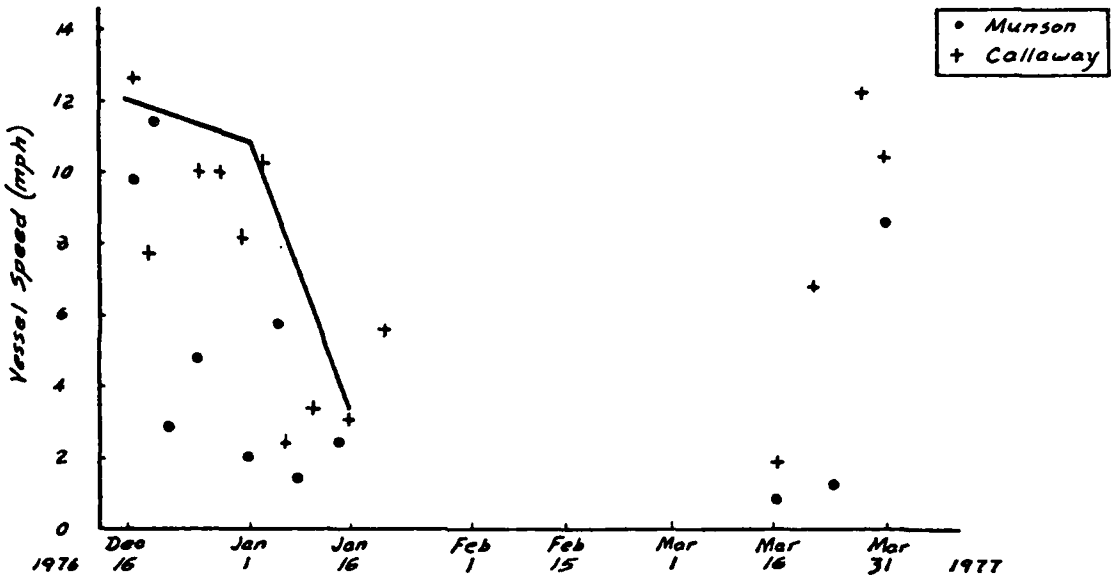
APPENDIX D

TRANSIT TIME VALIDATION/COMPARISON STUDY IN THE ST. MARYS RIVER

Figures D.1 and D.2 show actual transit times for the bulk carriers MUNSON and CALLOWAY during the winter of 1976-77 and for the MUNSON, CALLOWAY, and CLARKE during the winter of 1977-78. The transit times were extracted from the vessel logs by noting the times when transiting Detour Passage and the Soo Locks. Since temperature data and information on the traffic level were available for the winter of 1976-77, the computer model for ship transit through the St. Marys River was run and the results are shown as the solid line in Figure D.1. Examination of the figures show that the transit time and average vessel speed varied a great deal both between ships and between trips for the same ship. The model results do not show the same variability. The model assumes that the ships were equally spaced in time. This assumption breaks down at the low level traffic levels actually experienced during the historical winters of 1976-77. The relatively fast speeds and short transit times may occur because the ship is following a more capable ship in ice. The slower speeds and long transit times may be due to following a less capable ship or a ship that has become stuck and requires assistance. Delays may also occur due to traffic routing which requires that the ship wait for its turn through the lock.

Given all of these possible sources of variability, which may still apply at the traffic levels predicted for the year 2000 A.D., the model reasonably predicts the speed and transit time for the CALLOWAY in the winter of 1976-77. It is interesting to note that the MUNSON, a virtually identical ship to the CALLOWAY, is consistently slower. This difference may be ascribed to the experience and ability of the vessel master in ice clogged channels.

Figure D.1 St. Marys River — Actual Transits — 1976-1977



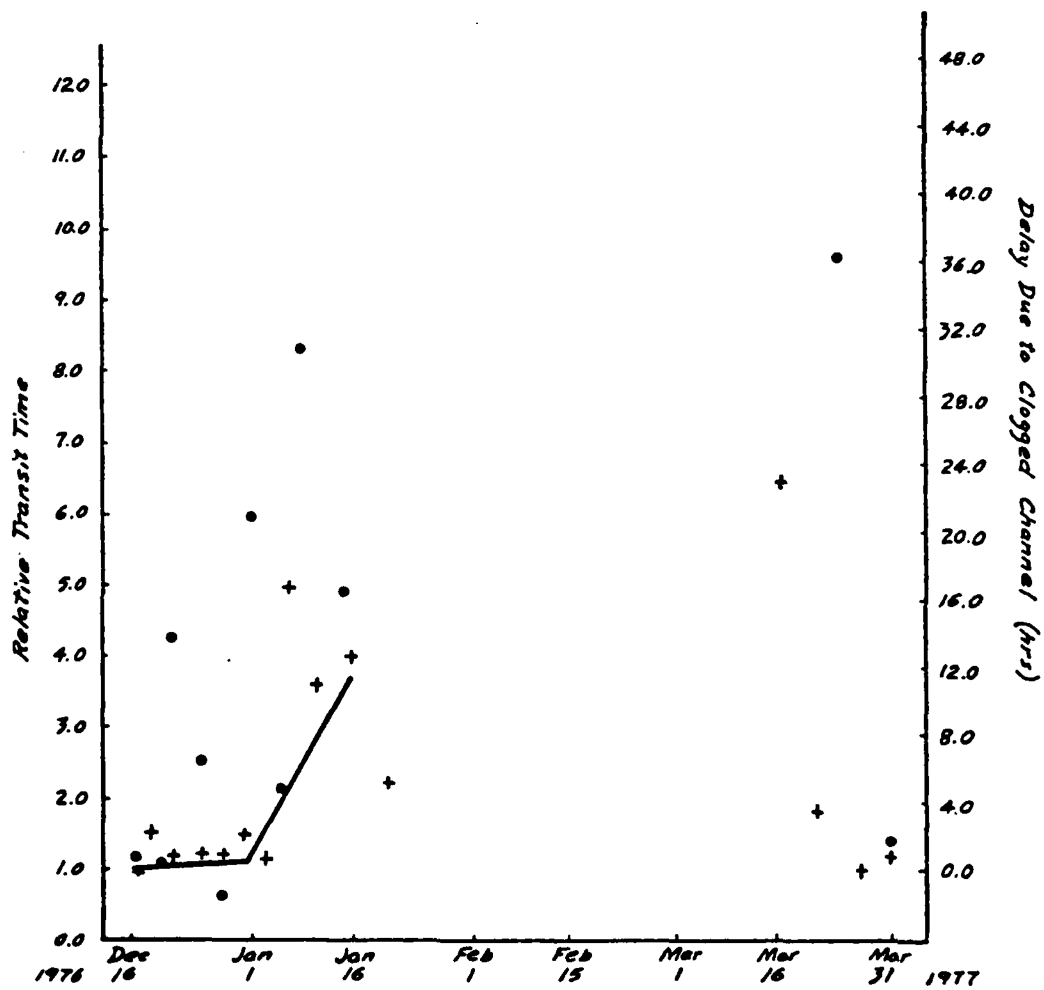
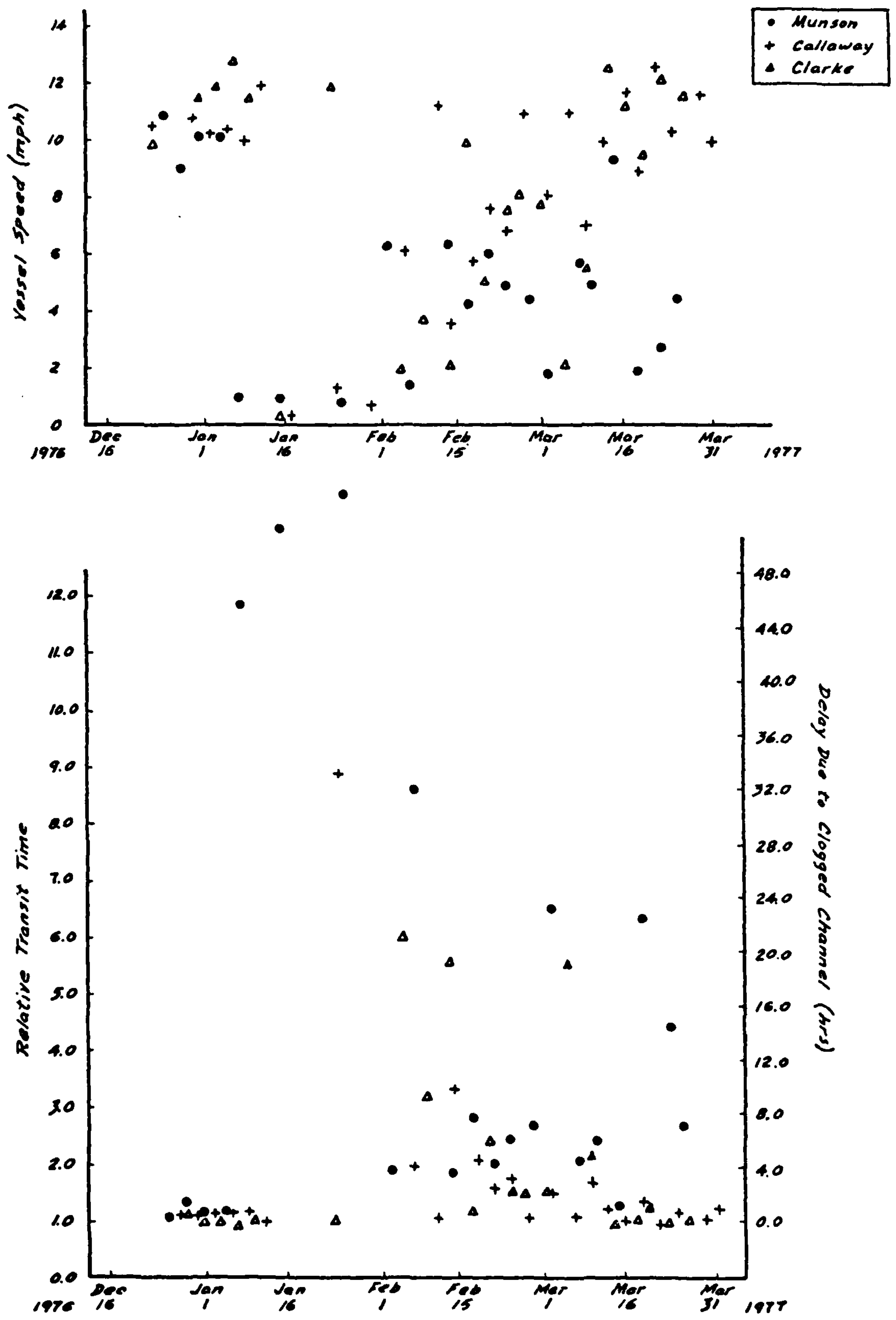


Figure D.2. St. Marys River — Actual Transits — 1977-1978



APPENDIX E

BIWEEKLY TRANSIT TIME STUDY

APPENDIX E

BIWEEKLY TRANSIT TIME STUDY

E.1 St. Marys River

The simulation described in Appendix C, which included vessel thrust, vessel resistance in ice, and the accelerated growth of ice in the ship track, was expanded to explicitly include the analysis of ship maneuverability through the four turns likely to cause problems on the St. Marys River. Delays in the turns were considered in the calculation of transit time for this study and all three ship types (Section 3.3) were evaluated. The interval used in this study is two weeks (14, 15, or 16 days) and, therefore, the daily freezing degree-day value is the average of the actual values over that period, as in the previous studies.

Figures E.1 through E.5 show the results of this simulation for the three representative vessels in the severe, colder, average, milder, and mild winters used in the previous studies. The upper graph in each pair of figures presents the average vessel speed in the straightaways. For the severe, colder, and average winters, the Class 5 vessel will become stuck in the straightaways without channel clearing or icebreaker assistance. The lower figures show that, in all but the most mild winter, the Class 5 vessel will eventually exceed a delay of twelve hours due to its slow passage through the straightaways. In no case do the Class 7 and Class 10 vessels ever become stuck in the straightaways or exceed a delay of twelve hours due to slow speed in the straightaways. Twelve hours was chosen as a reasonable maximum acceptable delay for this study.

In addition to the vessel delay in the straightaways, the lower figures presented in Figures E.1 through E.5 include the delays due to maneuvering through the turns. The delays due to the turns were taken from Figure B.8 and added to the delays in the straightaways. In all five winters the Class 5 vessel vecomes stuck in the turns with no channel clearing, while the Class 7 vessel becomes stuck in the turns in the severe and colder winters.

E.2 St. Lawrence River

The simulation was run for the International Section of the St. Lawrence River for the three ships listed in Section 3.3. The same severe, colder, average, milder, and mild winters were used. Only one turn, around Carleton Island close to Lake Ontario, was identified as being a possible problem area. In an analysis of vessel maneuverability it was concluded that no significant amount of time need be lost for brash ice thicknesses less than 48 inches since the channel is much wider than in the St. Marys River.

The results of the simulation are presented in Figures E.6 through E.10. In no case is the Class 7 Salty seriously affected by the brash ice in the straight shipping channel. In the absence of channel clearing, the 8000 SHP

Class 7 Laker is predicted to become stuck in the straightaways in the severe, colder, and average winters. The less powerful 7200 SHP Class 7 Laker, the least capable vessel allowed on the Seaway under the current Seaway restrictions, becomes stuck in the straightaways approximately a week to ten days before the 8000 SHP Laker. In addition, the least capable ship also becomes stuck late in the milder winter.

When the brash ice thickness exceeds 48 inches, the Class 7 Lakers may become stuck in the turn around Carleton Island. This is indicated by the vertical dotted line in the lower figure of each pair. In the absence of channel clearing, the Class 7 Lakers may become stuck in all but the most mild winter. The Class 7 Salty will become stuck in the turn late in the severe winter only.

Figure E.1. St. Marys River - Severe Winter - 1969-1970

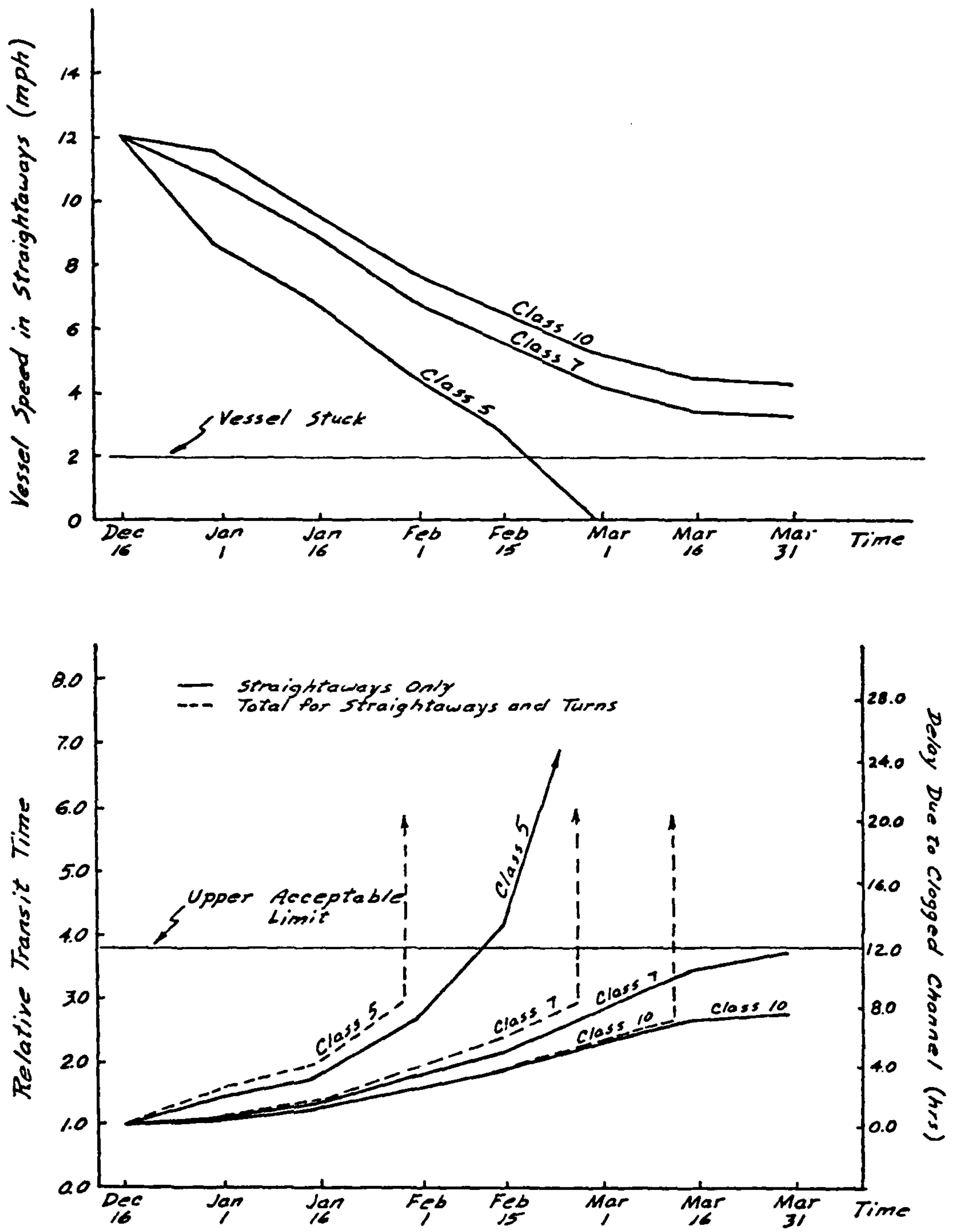


Figure E.2. St. Marys River — Colder Winter — 1976-1977

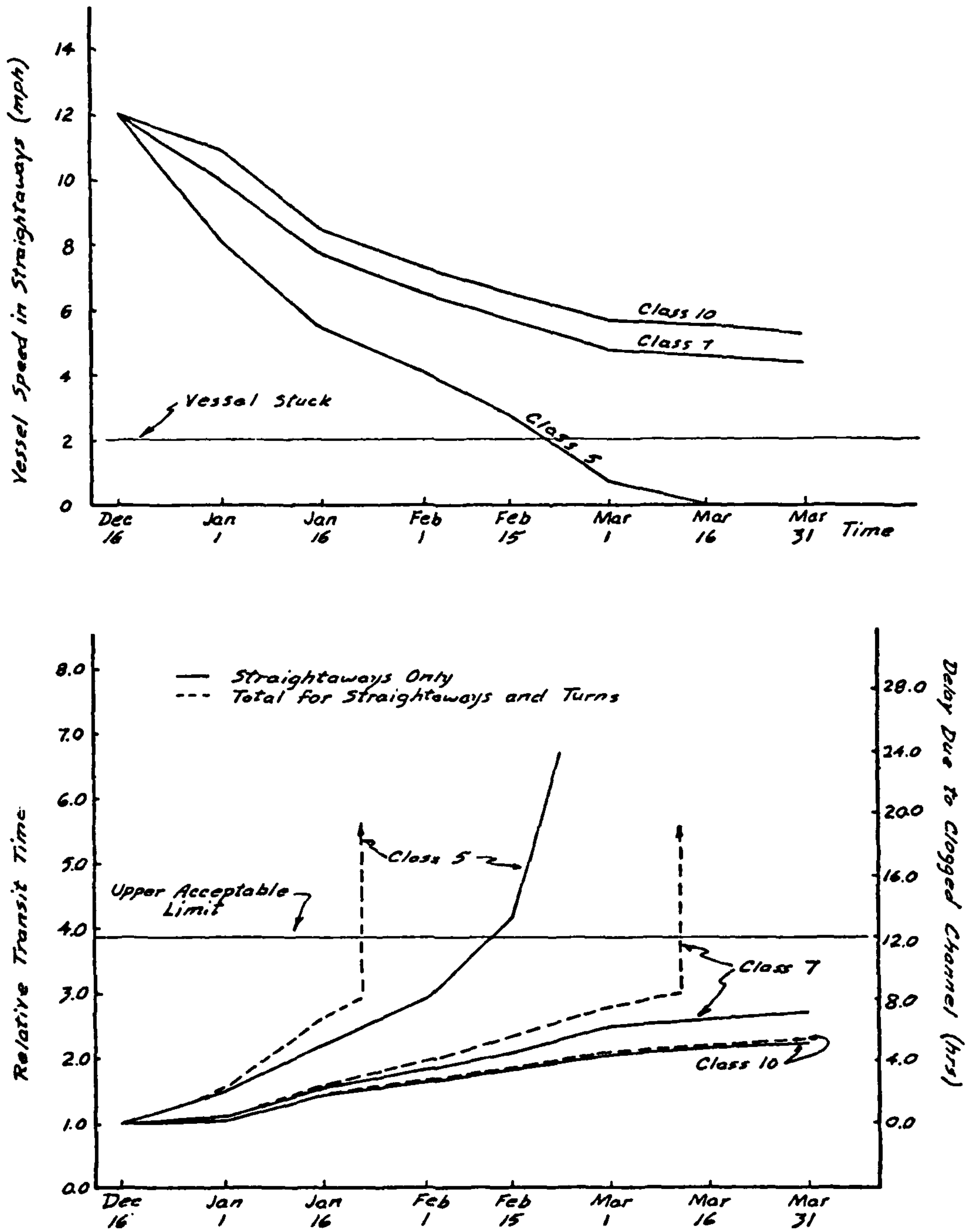
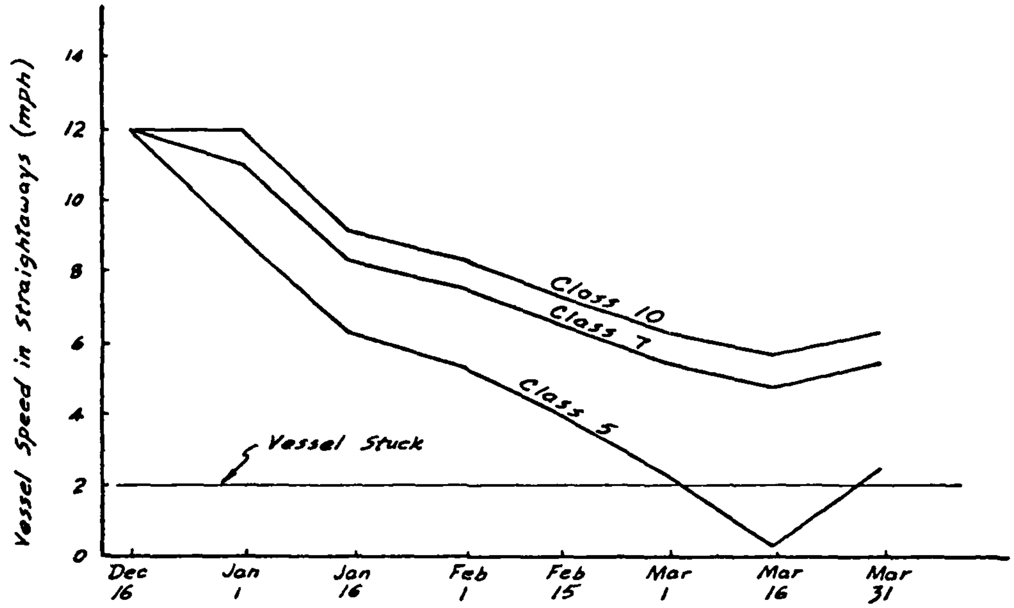


Figure E.3. St. Marys River — Average Winter — 1968-1969



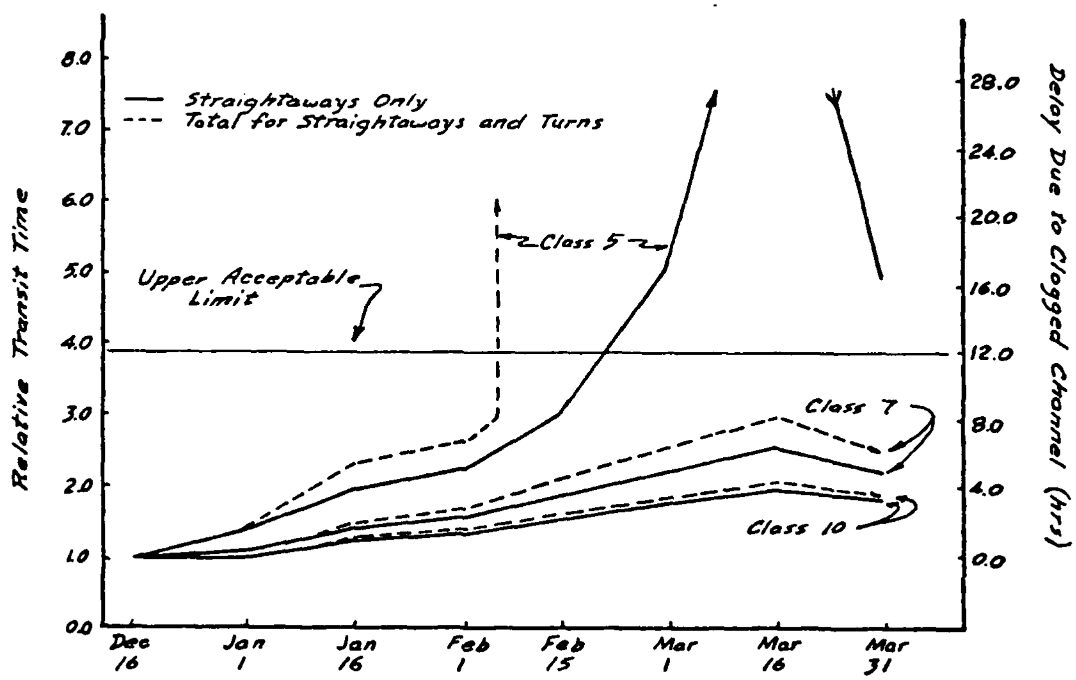
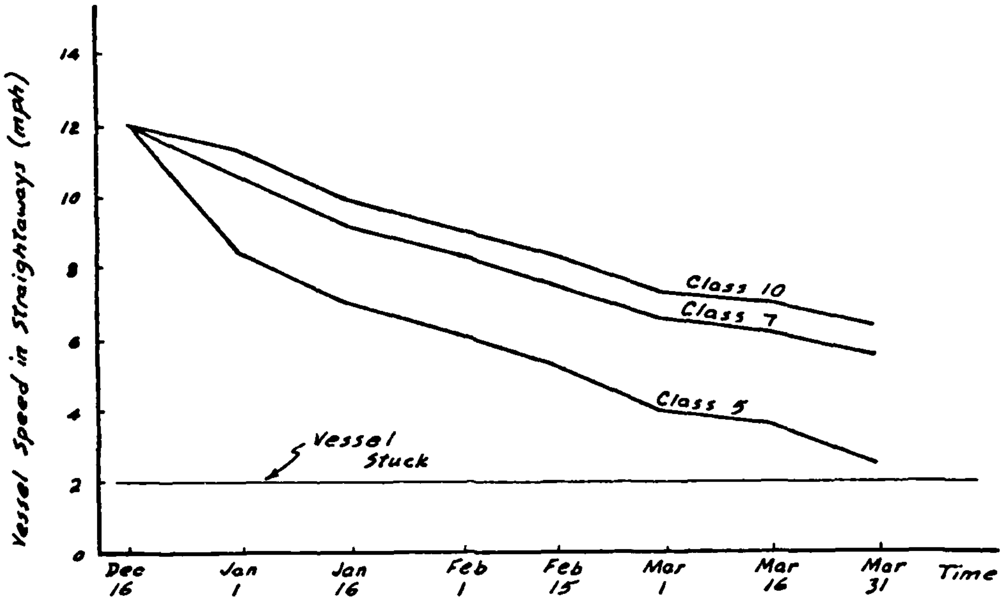


Figure E.4 St. Marys River — Milder Winter — 1965-1966



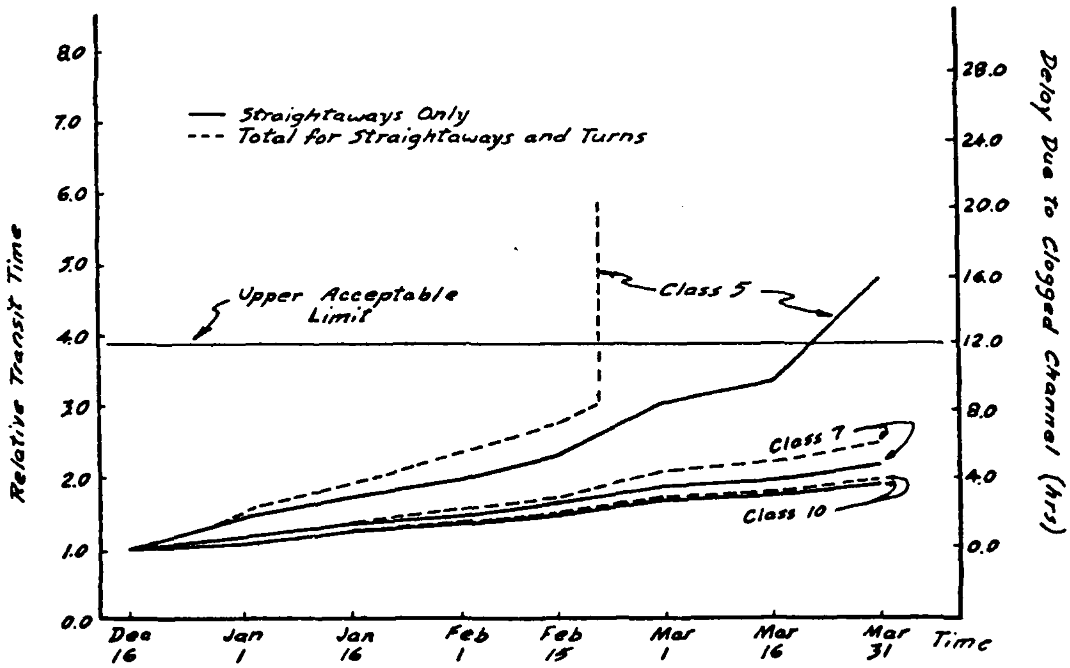
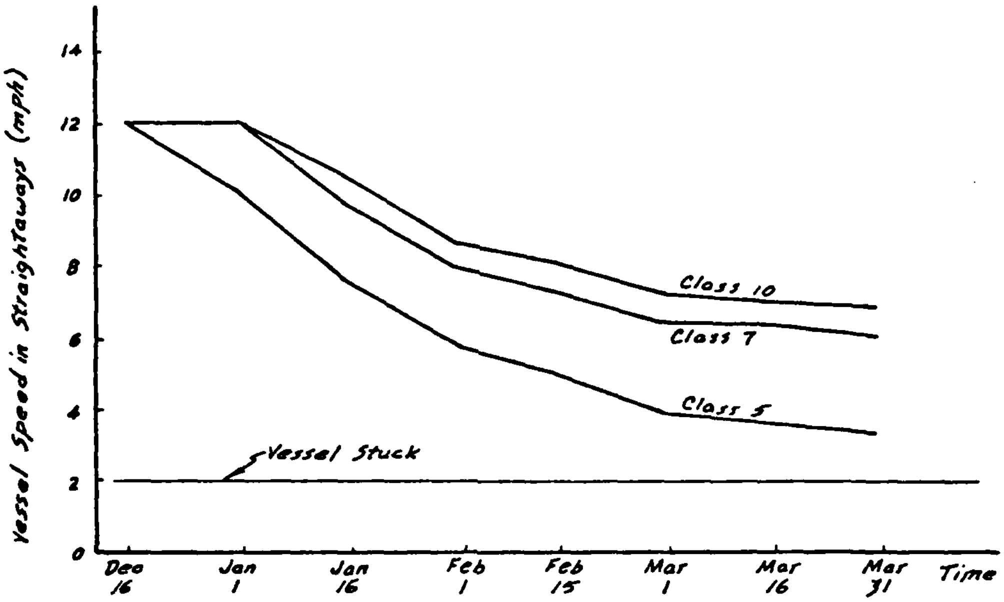


Figure E.5. St. Marys River — Mild Winter — 1952-1953



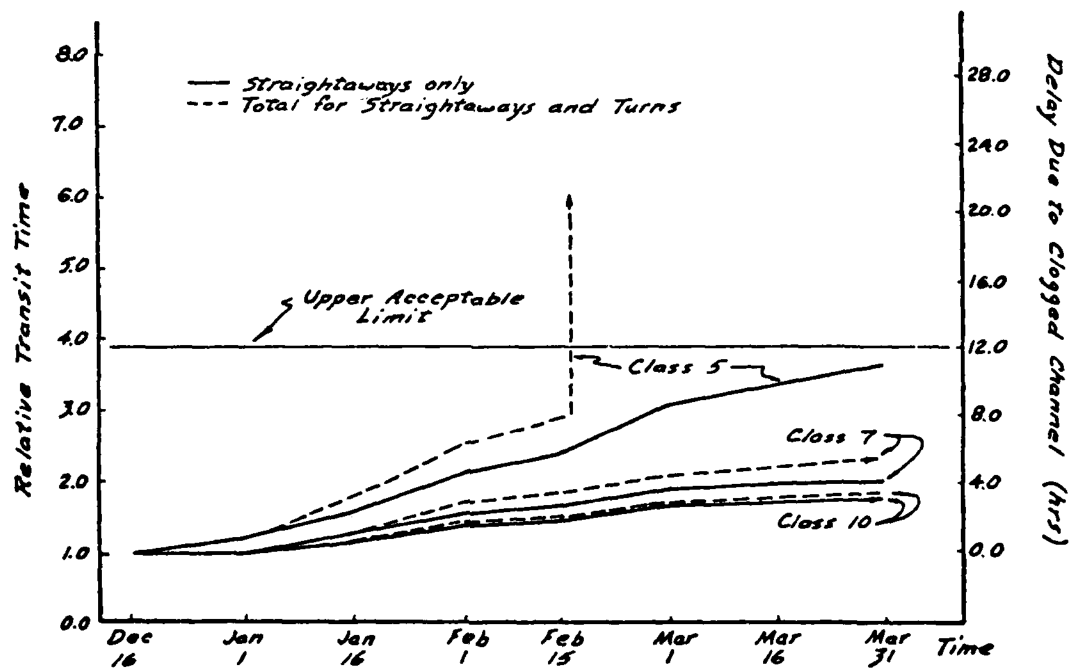
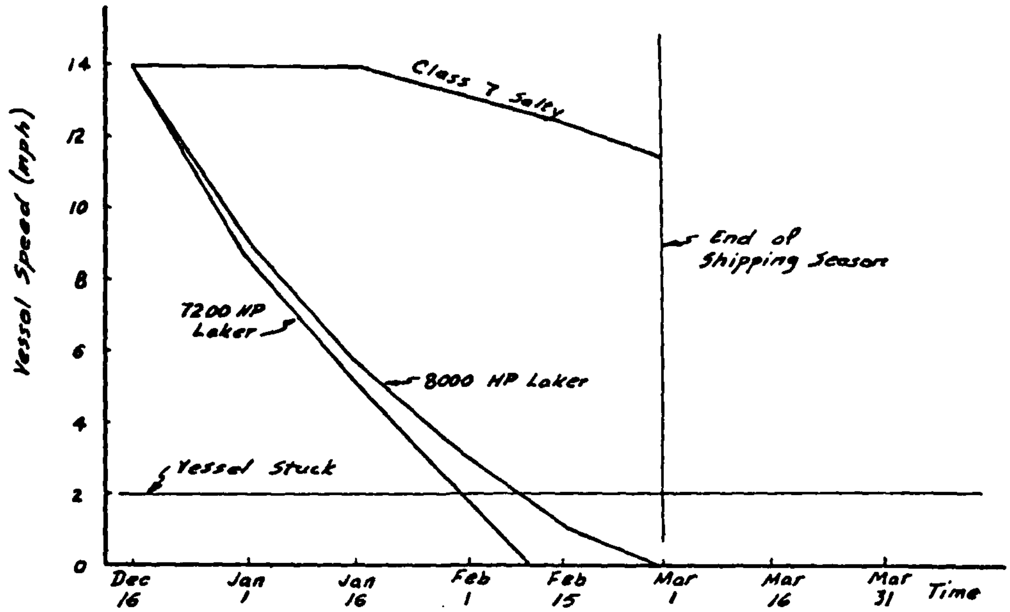


Figure E.6. St. Lawrence Seaway — Severe Winter — 1969-1970



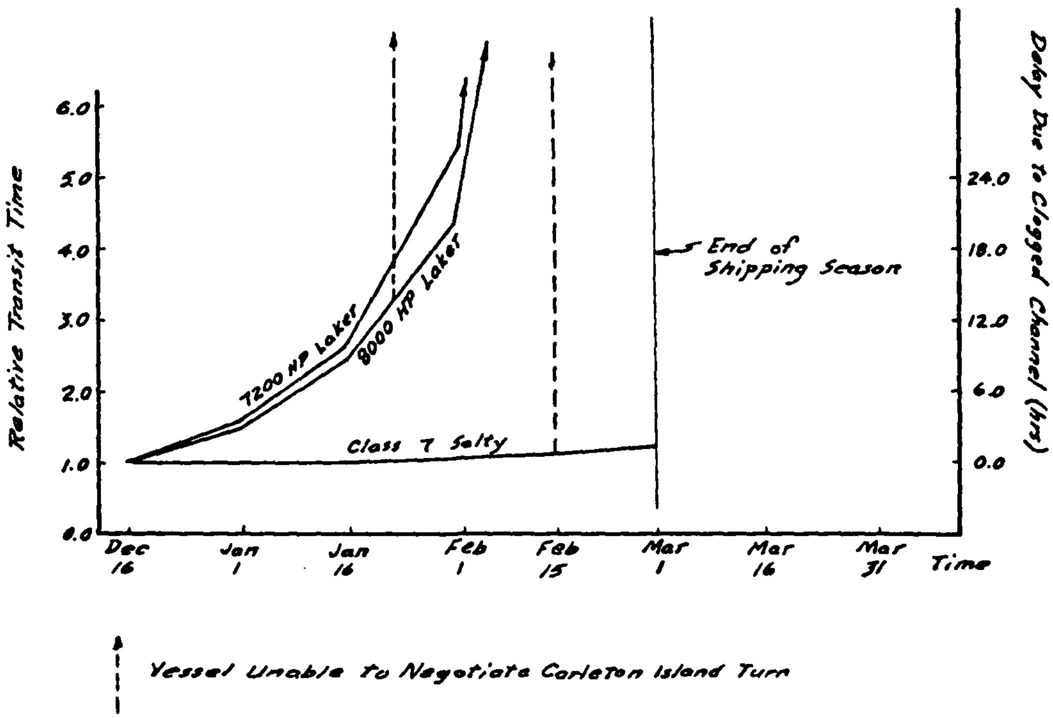


Figure E.7. St. Lawrence Seaway — Colder Winter — 1967-1968

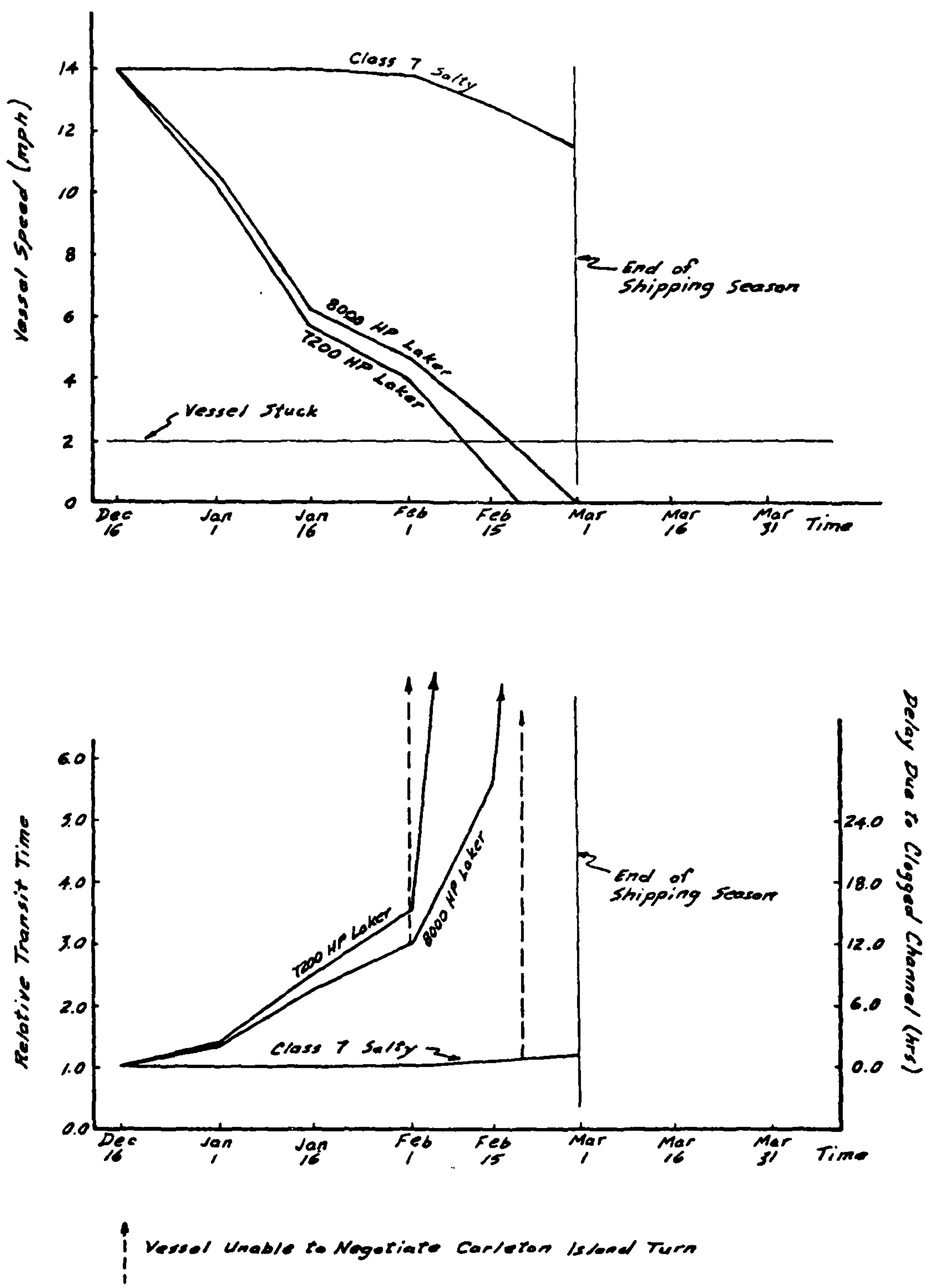
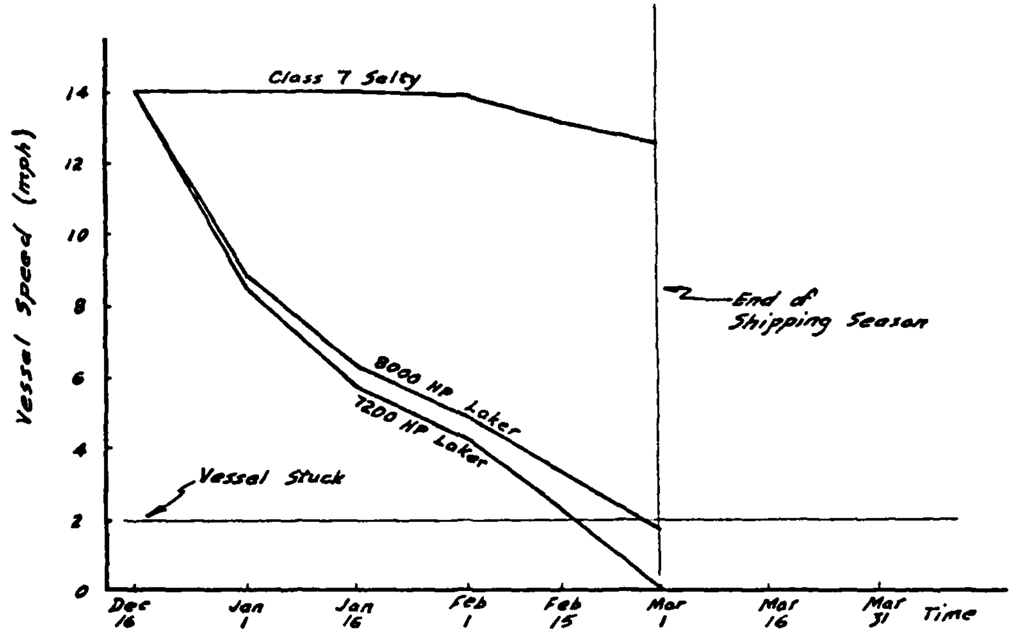


Figure E.8. St. Lawrence Seaway — Average Winter — 1968-1969



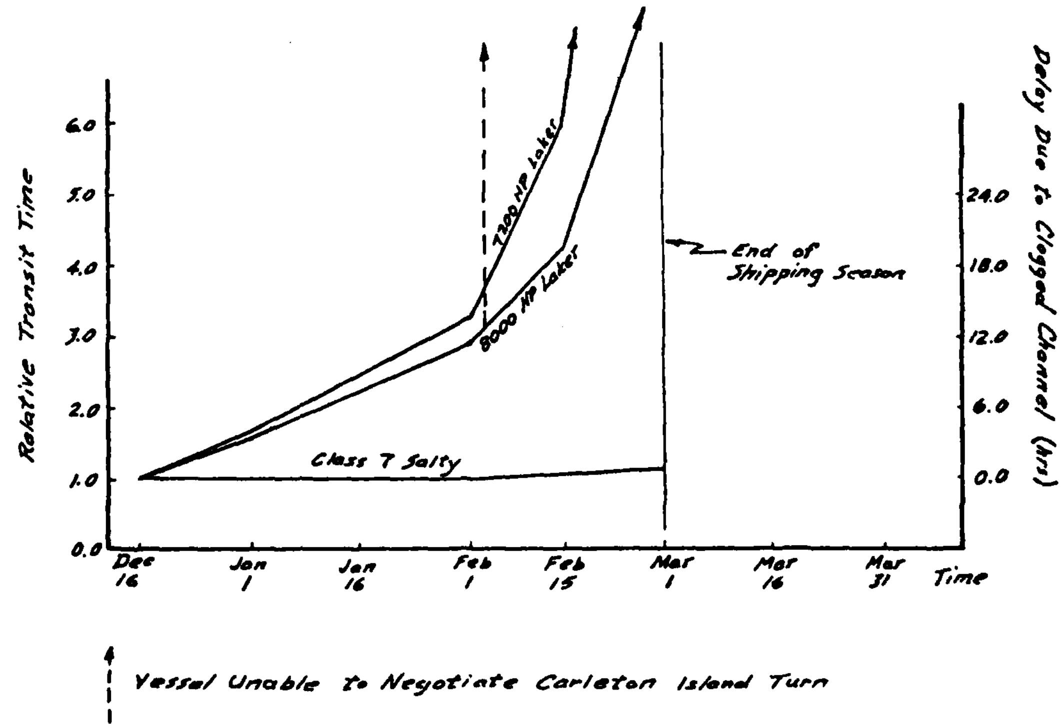
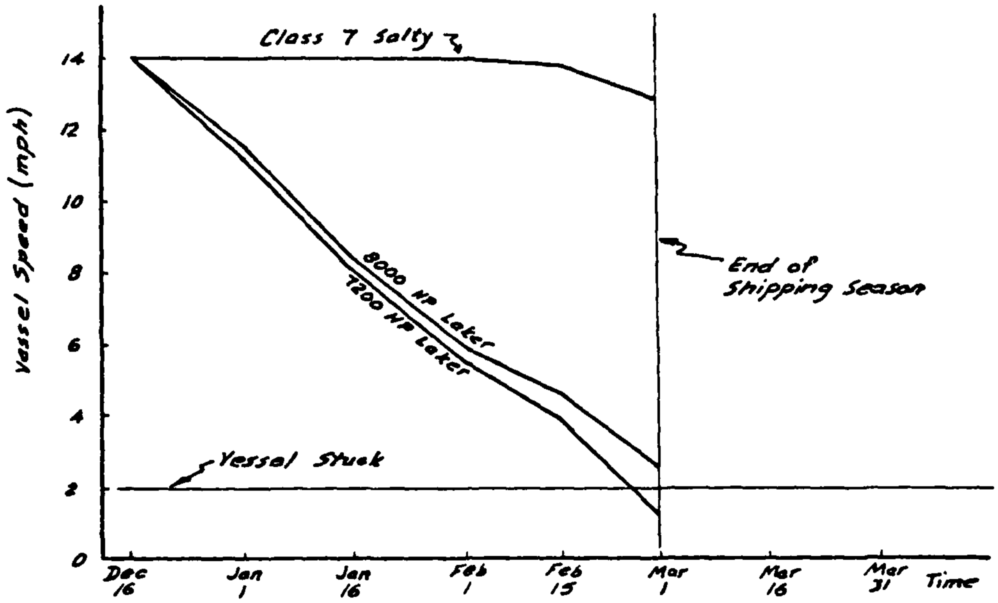
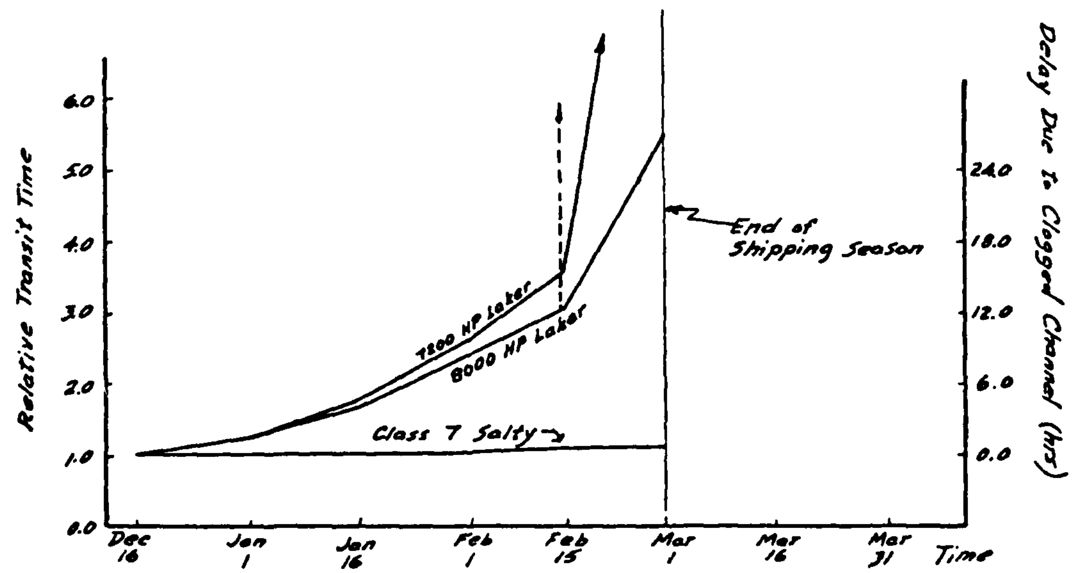


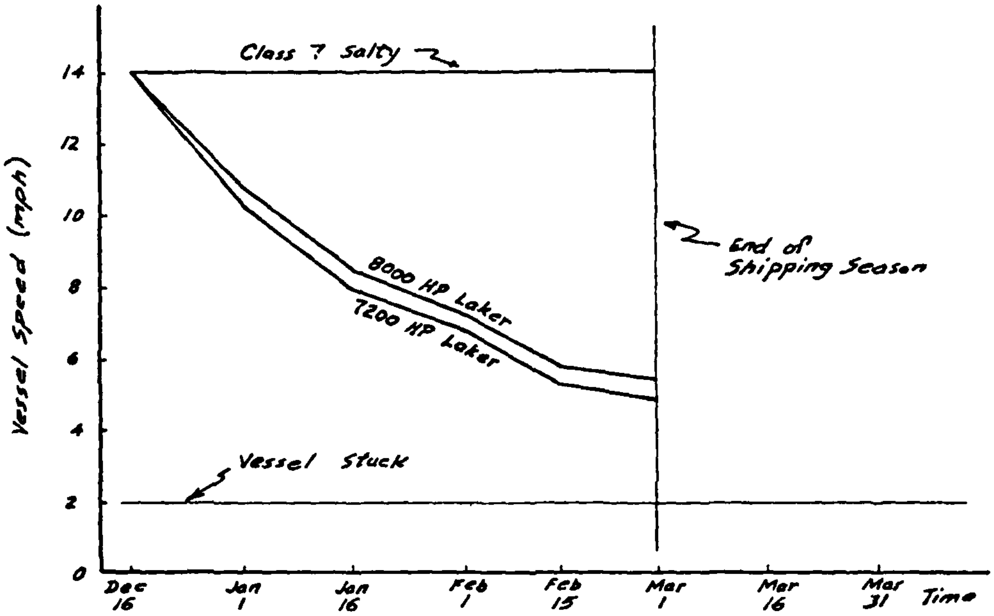
Figure E.9. St. Lawrence Seaway — Milder Winter — 1965-1966

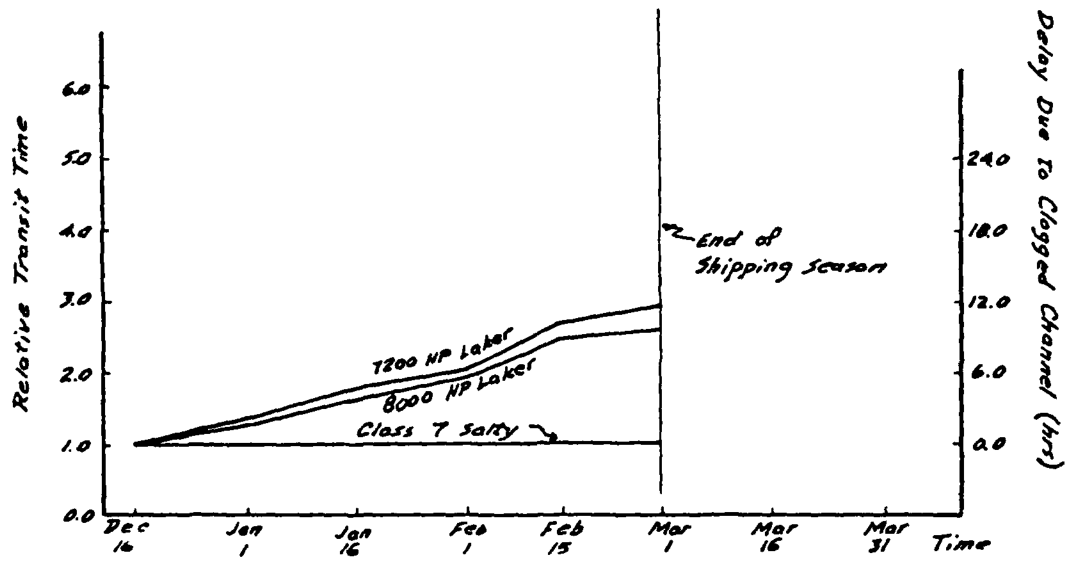




Vessel Unable to Negotiate Carleton Island Turn

Figure E.10. St. Lawrence Seaway — Mild Winter — 1952-1953





APPENDIX F

BIWEEKLY REMOVAL RATE STUDY

APPENDIX F

BIWEEKLY REMOVAL RATE STUDY

The study of Appendix E was redone using a limiting ice thickness. The limiting ice thickness for a given ship type was the thickness just before the ship became stuck. When the ice thickness reached the limiting thickness, the thickness was maintained at the limiting thickness and the daily growth rate of the ice, an estimated average, was recorded for the biweekly period. The removal rate required, therefore, equals the growth rate at the limiting thickness.

It should be noted that the least capable ship will limit the speed of those vessels following it. Therefore, the channel clearing requirement should be established for the least capable ship expected or allowed to transit the St. Marys River in the winter. Figure F.1 shows the amount of channel clearing in the straightaways required to maintain the Class 5 vessels and, therefore, all other vessels at a delay not to exceed 12 hours. This requirement is equivalent to maintaining a brash ice thickness not greater than 41 inches. Examination of Figure B.8 shows that the ice thickness must be maintained at less than 35 inches in the turns if the Class 5 ships are to avoid becoming stuck. Figure F.2 shows the ice removal rate in the turns to maintain navigation for each of the five winters for the Class 5 vessel. Also shown in Figure F.2 are the removal rates required to maintain the more capable Class 7 and Class 10 vessels.

It is recommended that the least capable ship for which the ice clogged channel clearing system for the St. Marys River should be designed is the Class 7 Laker. Choosing this vessel as the "design ship" eliminates the major requirements of clearing the straightaways. The channel clearing effort is pinpointed on the four major problem areas for the majority of the commercial fleet. The less capable 4,000 SHP, Class 5 Laker should not be the "design ship" because by the year 2000 A.D., it is anticipated that few of these vessels will be operating in the winter. The results of Kotras, et al., [5] indicate that no Class 5 vessels will be required to operate in the year 2000 in the winter through the St. Marys River to transport the projected commodity load. On the other hand, significant numbers of Class 7 and 8 vessels are expected to operate through the winters [5]. Channel clearing will be restricted to the four tight turns on the St. Marys River and the Class 7 vessel will be used in subsequent studies.

Since the two Class 7 Lakers considered in the simulation on the St. Lawrence River are nearly the same in terms of ice capability, only the channel clearing requirements to maintain the less powerful ship were considered. The Class 7 Salty was not considered because it does not require any significant channel clearing to maintain its speed near the open water speed limit for most of the time.

Figure F-1. St. Marys River — Volumetric Ice Removal Rate to Maintain Class 5 Movement in Straightaways

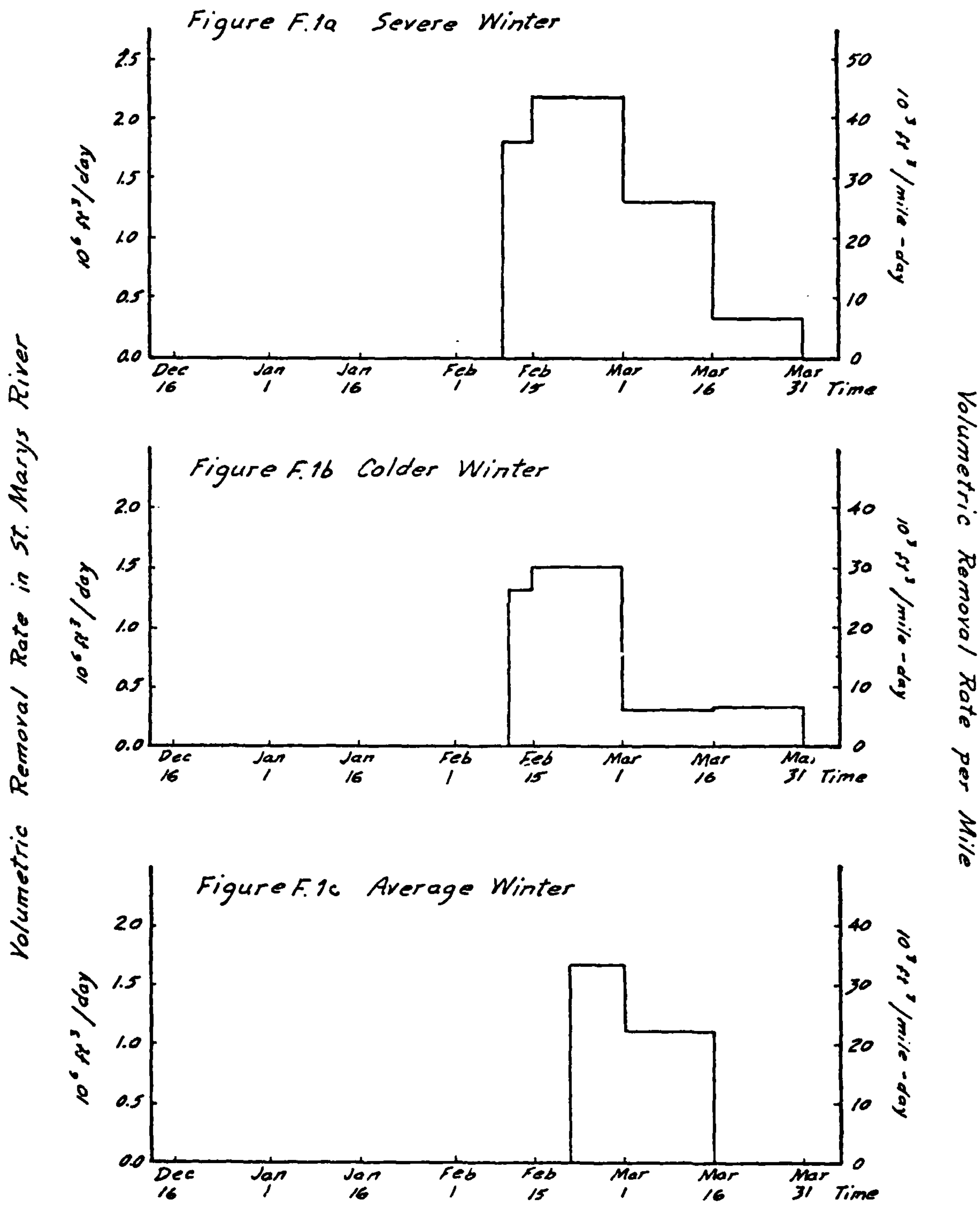
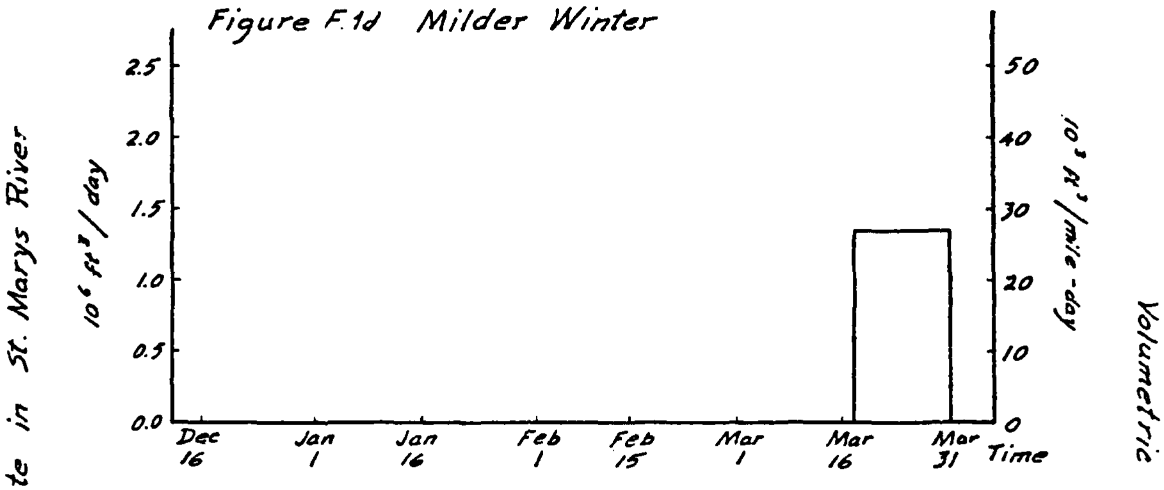
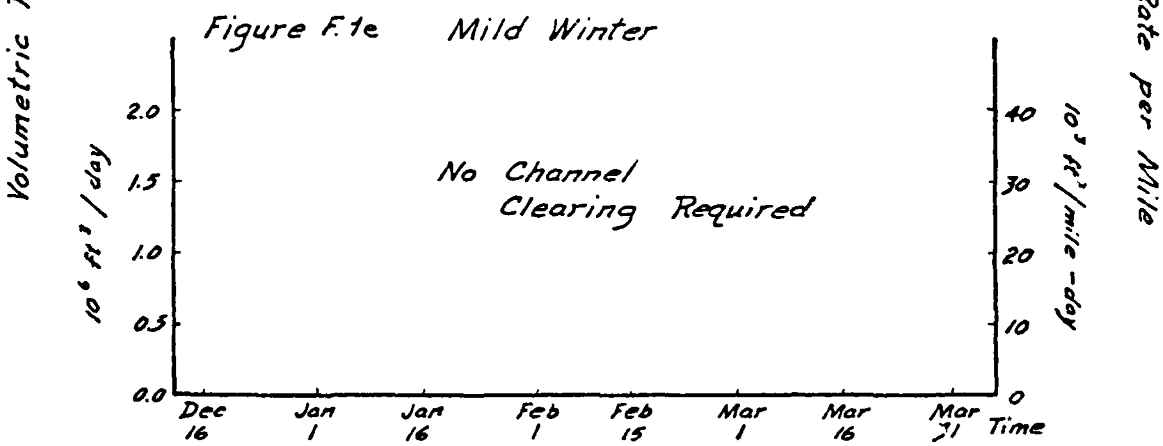


Figure F.1 contd. St. Marys River — Volumetric Ice Removal Rate to Maintain Class 5 Movement in Straightaways





AD-A104 671 ARCTEC INC COLUMBIA MD F/G 13/2
STUDY OF ICE CLOGGED CHANNEL CLEARING PROBLEMS.(U)
MAY 81 J W ST. JOHN, J L COBURN, T V KOTRAS DTCG38-80-C-80039
UNCLASSIFIED 569C-5 USCG-D-34-81 NL

AD A
104671

END
DATE
FILMED
10-81
DTIC

Figure F.2 St. Marys River — Volumetric Ice Removal Rate to Maintain Traffic in Turns

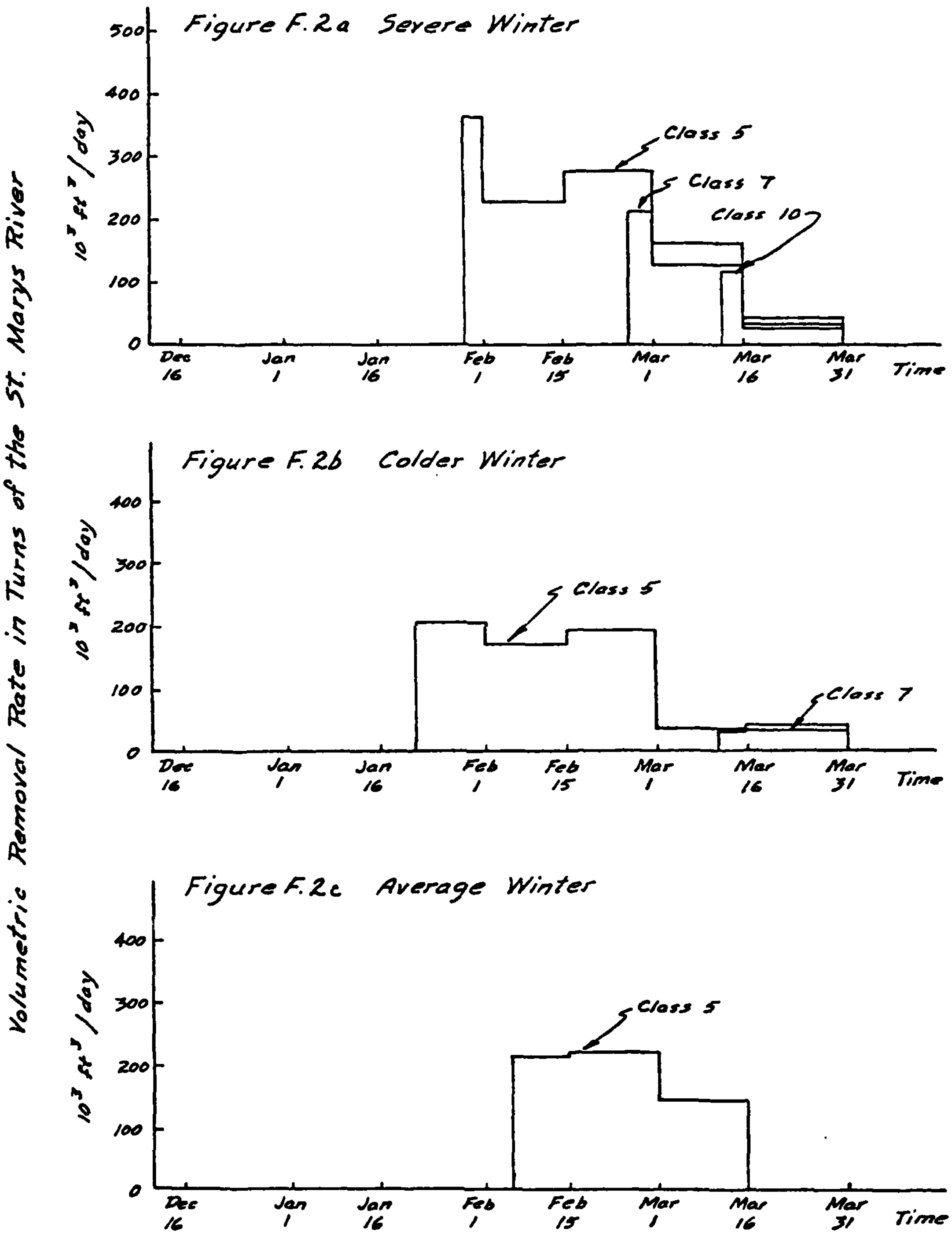


Figure F.2 contd. St. Marys River   Volumetric Ice Removal Rate to Maintain Traffic in Turns

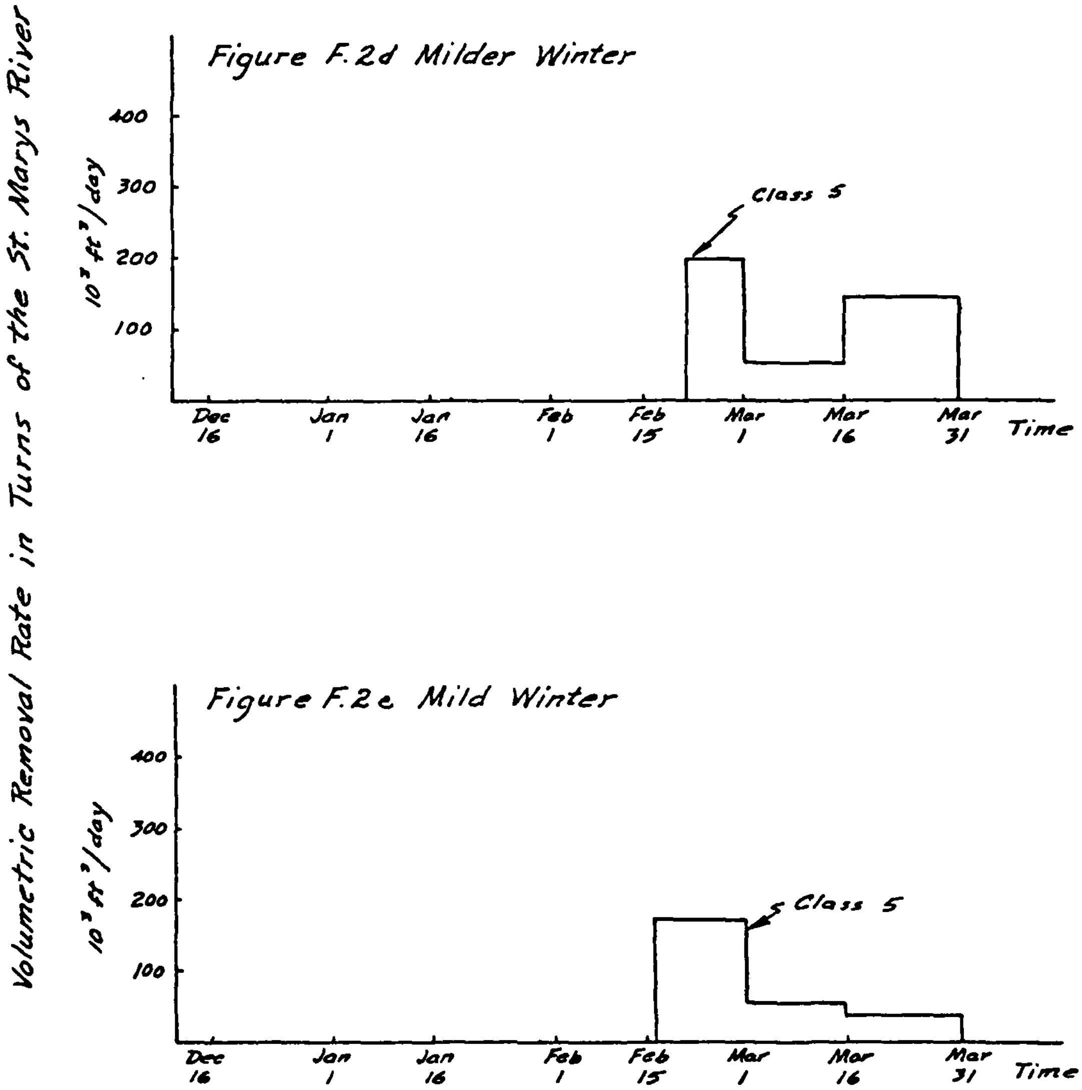
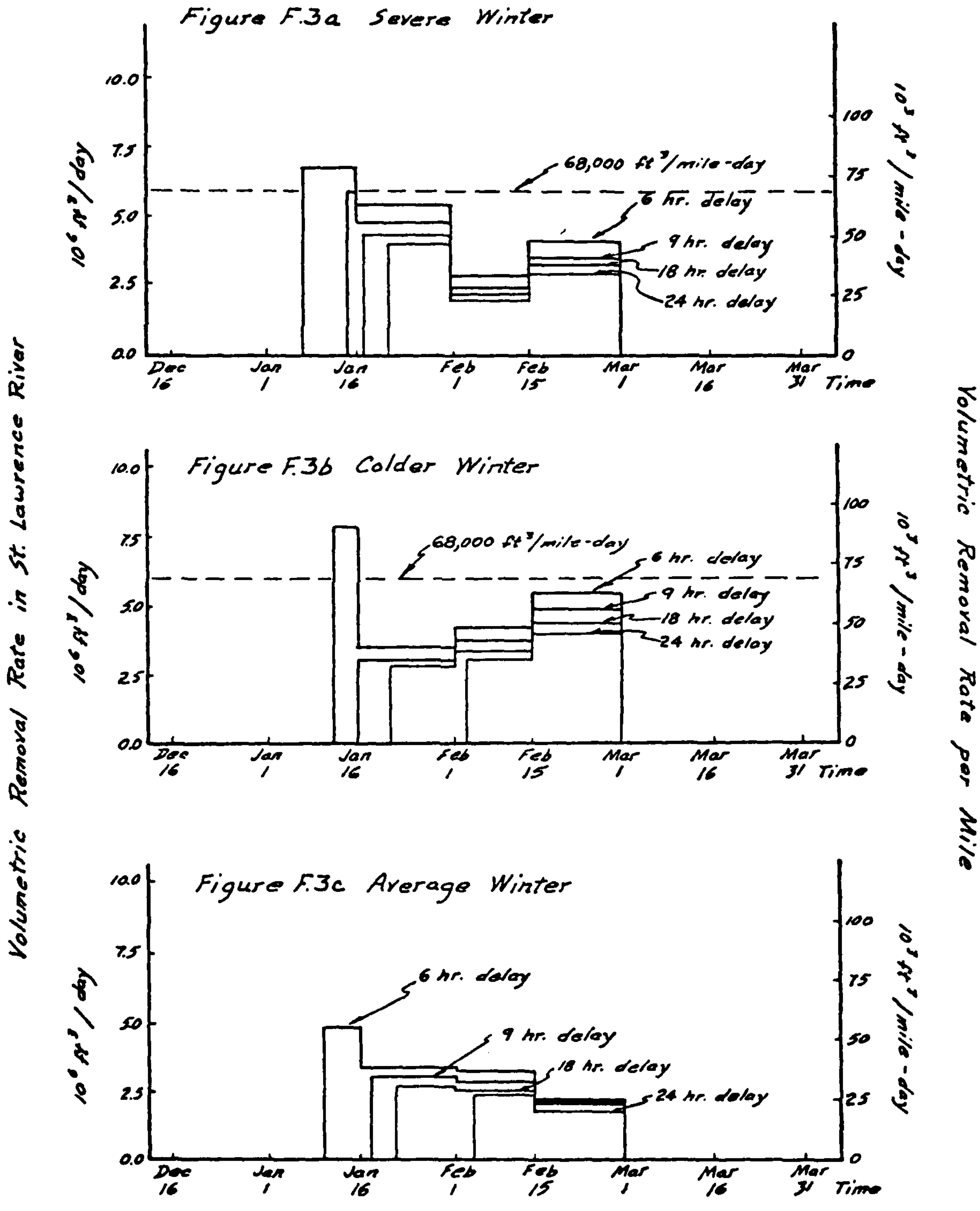


Figure F.3. St. Lawrence River — Volumetric Ice Removal Rate



No maximum acceptable delay has been established for vessel transiting the International Section of the St. Lawrence River; therefore, the volumetric channel clearing requirements to maintain delays of 6, 9, 18, and 24 hours have been computed. Figure F.3 shows the required ice removal rate to maintain these maximum delays for the least powerful ship for the severe, colder, average, milder, and mild winters. No special removal rate is needed for the Carleton Island Turn because the requirements for the 6 and 9 hour maximum delay maintain the ice thickness at a level less than that which will cause ships to become stuck. At the removal rate to maintain an 18 hour maximum delay, the removal rate in the turn needs to be only 3% greater than in the straightaways. At the removal rate to maintain a 24 hour maximum delay, the removal rate needs to be 10% greater than in the straight channels.

It is recommended that the maximum ice removal rate needed to maintain a maximum delay of 9 hours be used. At a rate of 68,000 ft^3/mile-day, the simulation indicates that the design vessel will never exceed a nine hour delay. Examination of the results presented in Figure F.3 reveals that at this removal rate the six hour delay will be exceeded for 9 days in the severe winter and 4 days in the colder winters. For the rest of the time, the delay due to ice will be 6 hours or less.

Figure F.3. contd. St. Lawrence River — Volumetric Ice Removal Rate

Figure F.3d Milder Winter

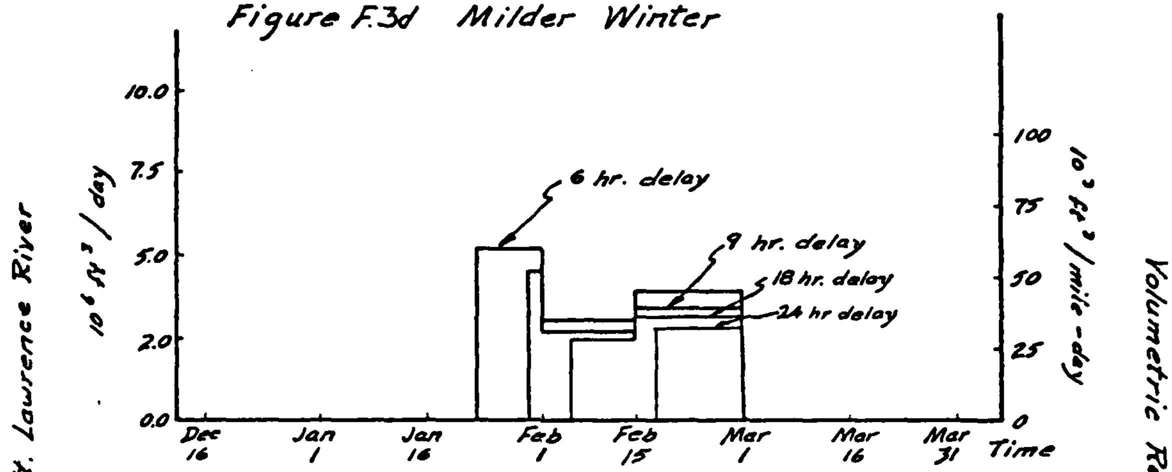
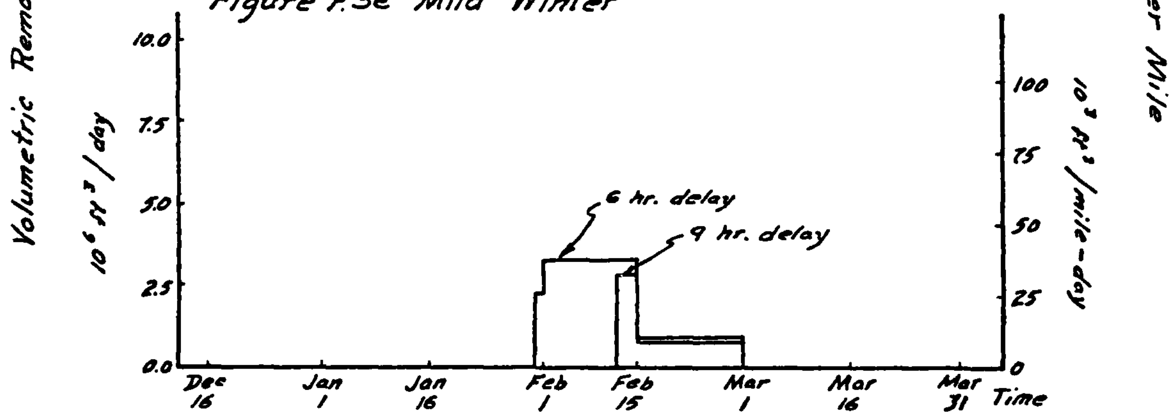


Figure F.3e Mild Winter



APPENDIX G

DAILY/BIWEEKLY REMOVAL RATE COMPARISON

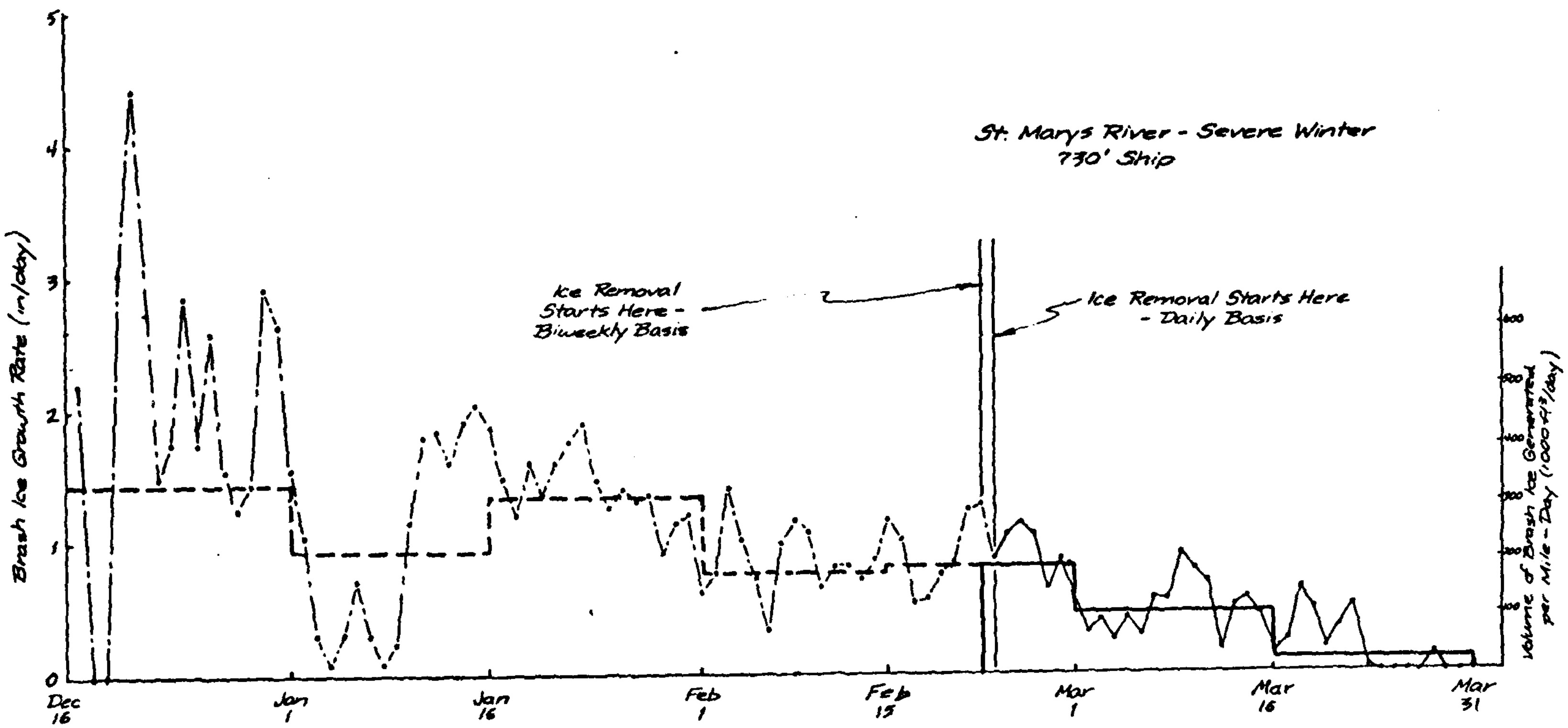
APPENDIX G

DAILY/BIWEEKLY REMOVAL RATE COMPARISON

This study was done to determine the validity of using a biweekly model to predict required removal rate. The same ship type, a 730 foot 8,000 SHP Laker on the St. Marys River and a 730 foot 7,200 SHP Laker on the St. Lawrence River, was run for both a biweekly and a daily time period. Results are presented for all five winters on both rivers in Figures G.1 through G.10.

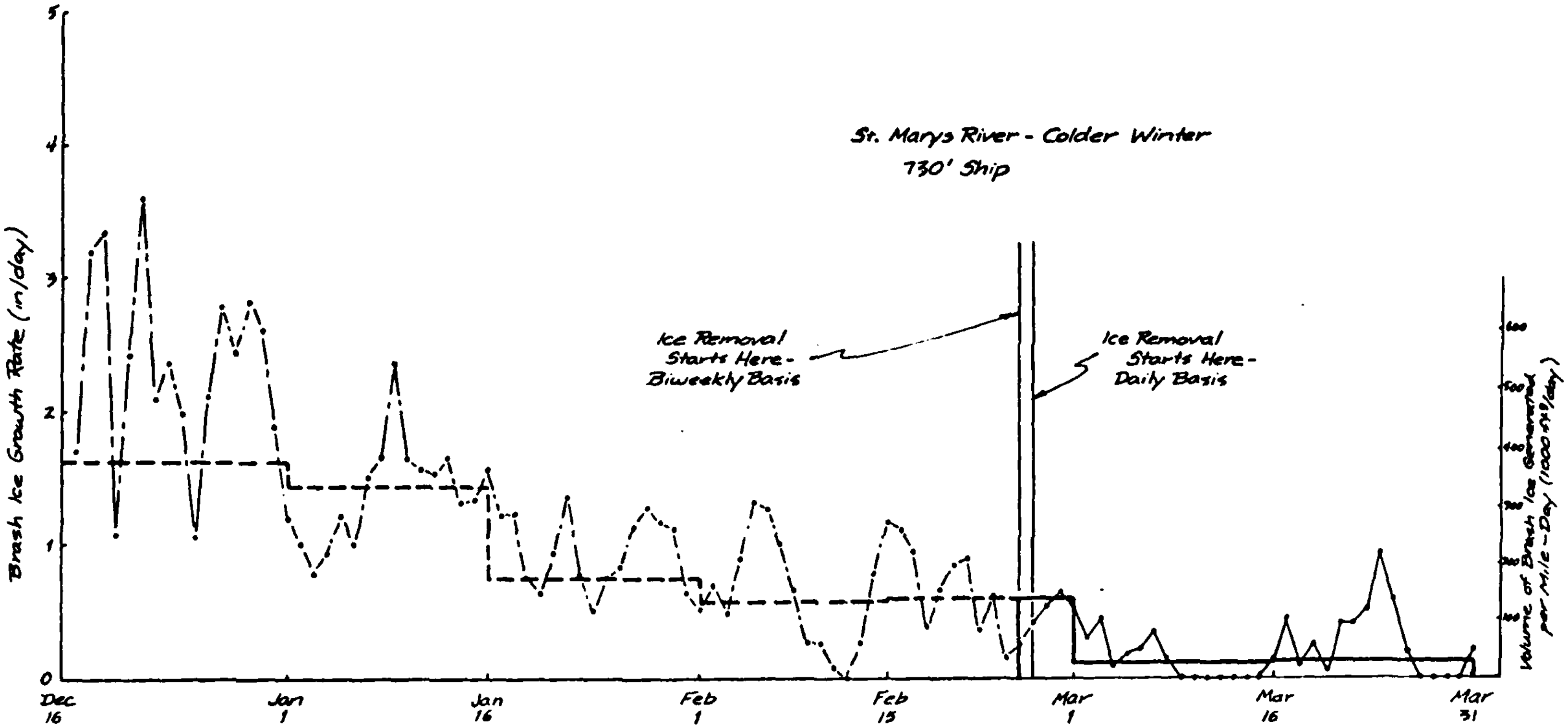
For the daily analysis, the model uses the actual daily FDD value to calculate ice growth but, in the biweekly analysis, the growth rate for each day in the biweek is calculated using an average FDD value for the biweek. The biweekly analysis should, therefore, predict an average value of growth rate or removal rate. The comparison shown in the figures indicates that the biweekly does in fact predict the average growth rate over the period, however, there is better agreement in late times than in the initial period where the ice grows rapidly. The start of removal is predicted fairly well; the biweekly scheme using the ice thickness at the ends of a biweekly period to interpolate the date where ice thickness reaches the removal point.

The fluctuations in the daily growth rate, however, are large and there is concern that a removal rate based on a biweekly analysis could underpredict delays. The conclusion of this study was that while the biweekly calculation provided reasonably accurate averages, there may be important effects from the variations. Therefore the daily method was used on all subsequent studies.



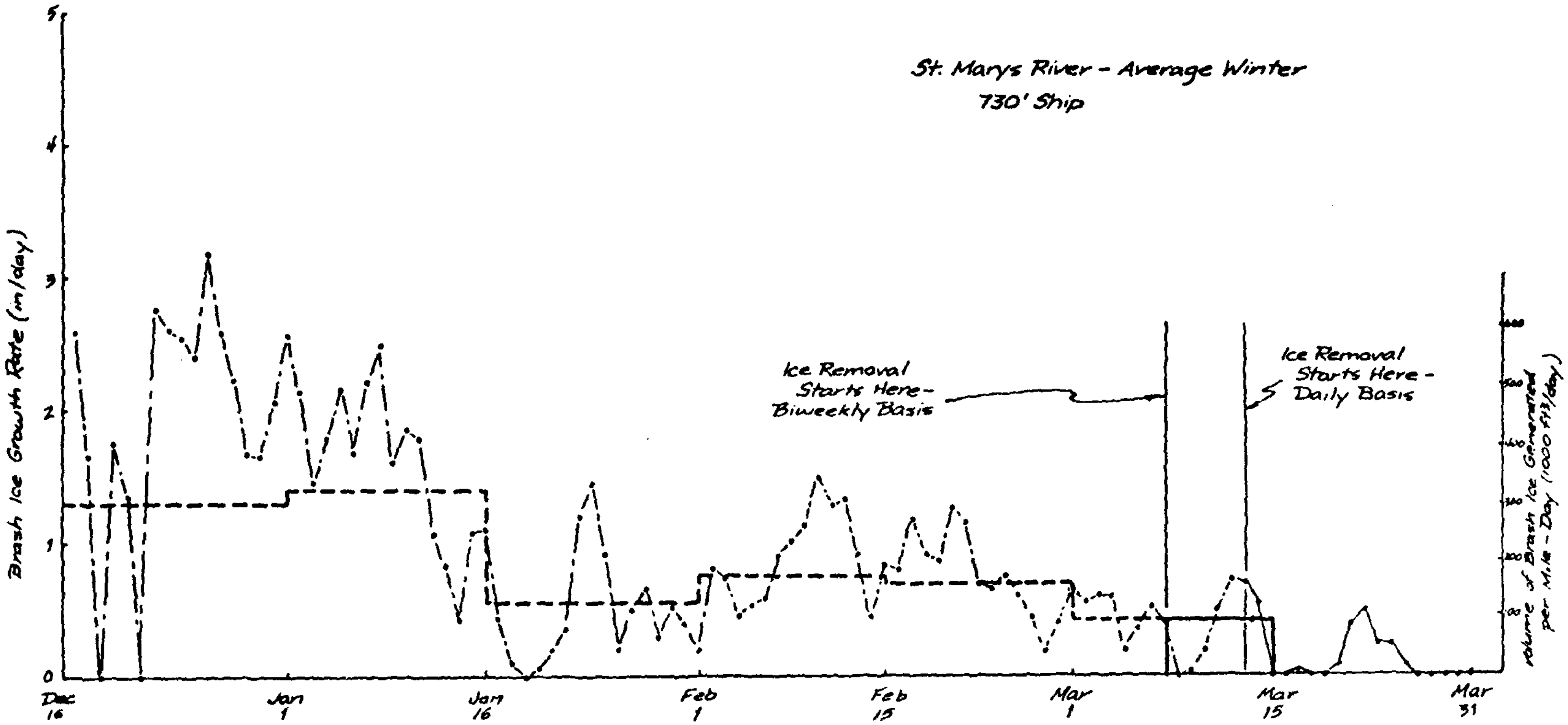
Brash Ice Removal Rate to Maintain Traffic in Turns
(Growth Rate = Removal Rate after 46 in. Ice Thickness is Reached)

Figure G.1



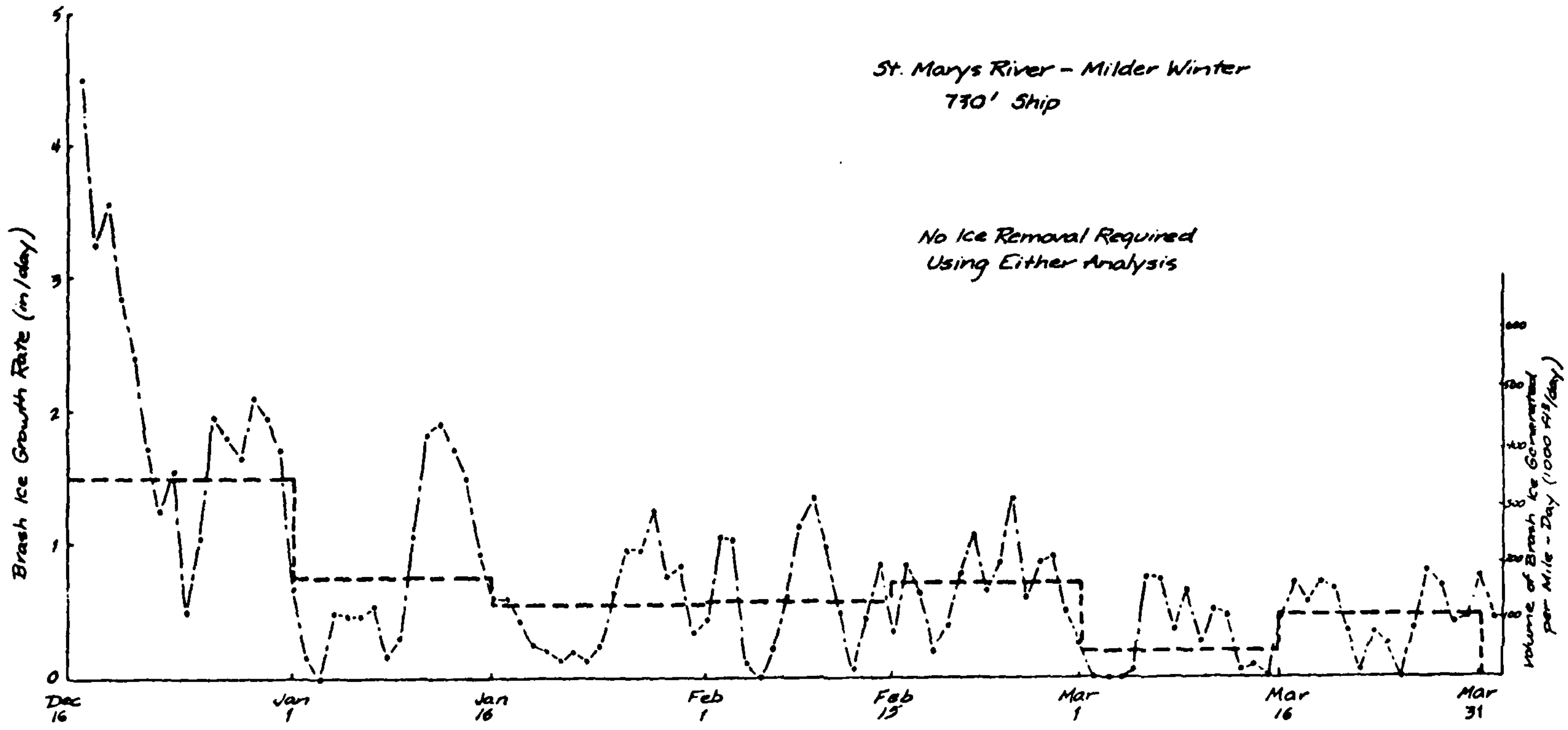
Brash Ice Removal Rate to Maintain Traffic in Turns
(Growth Rate = Removal Rate after 46 in. Ice Thickness is Reached)

Figure G.2.



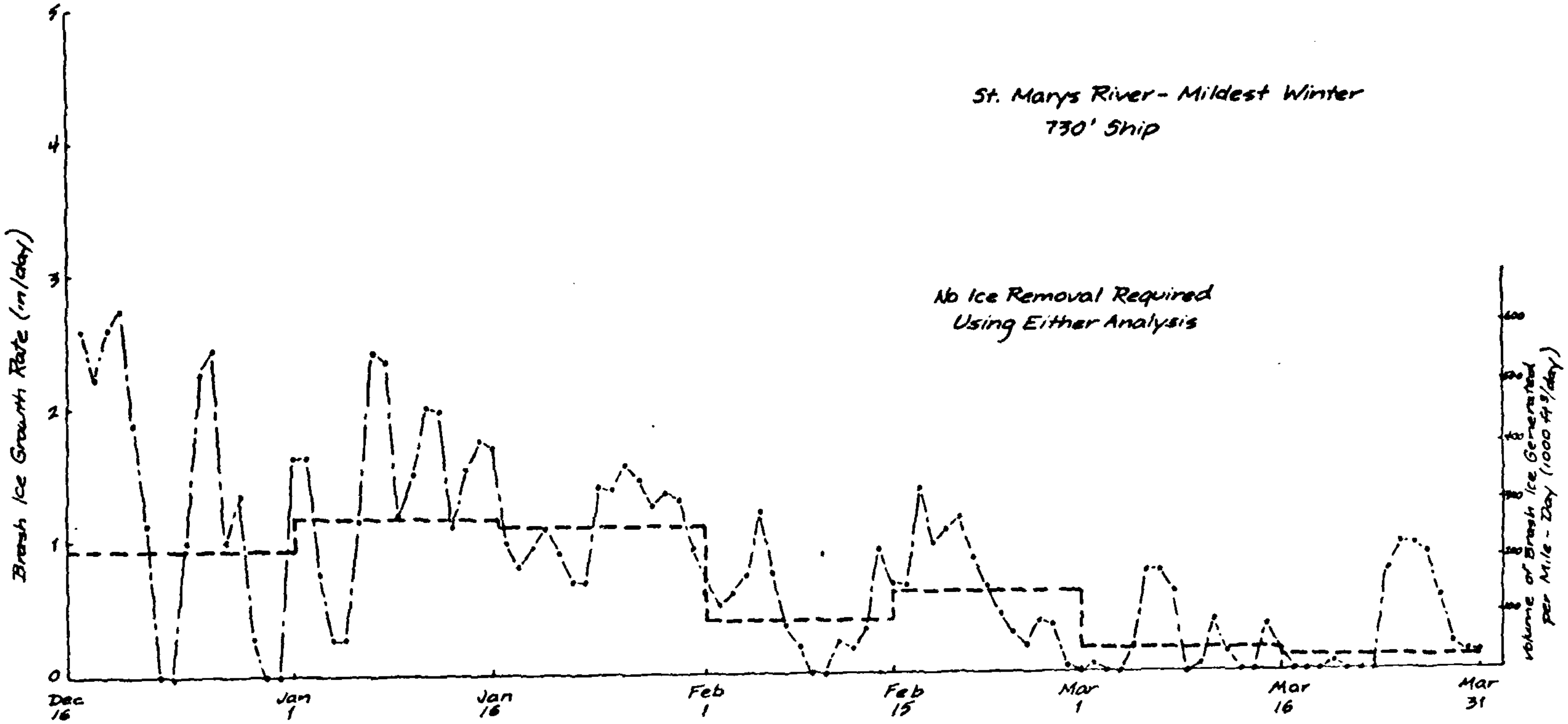
Brash Ice Removal Rate to Maintain Traffic in Turns
(Growth Rate = Removal Rate after 46 in. Ice Thickness is Reached)

Figure G.3



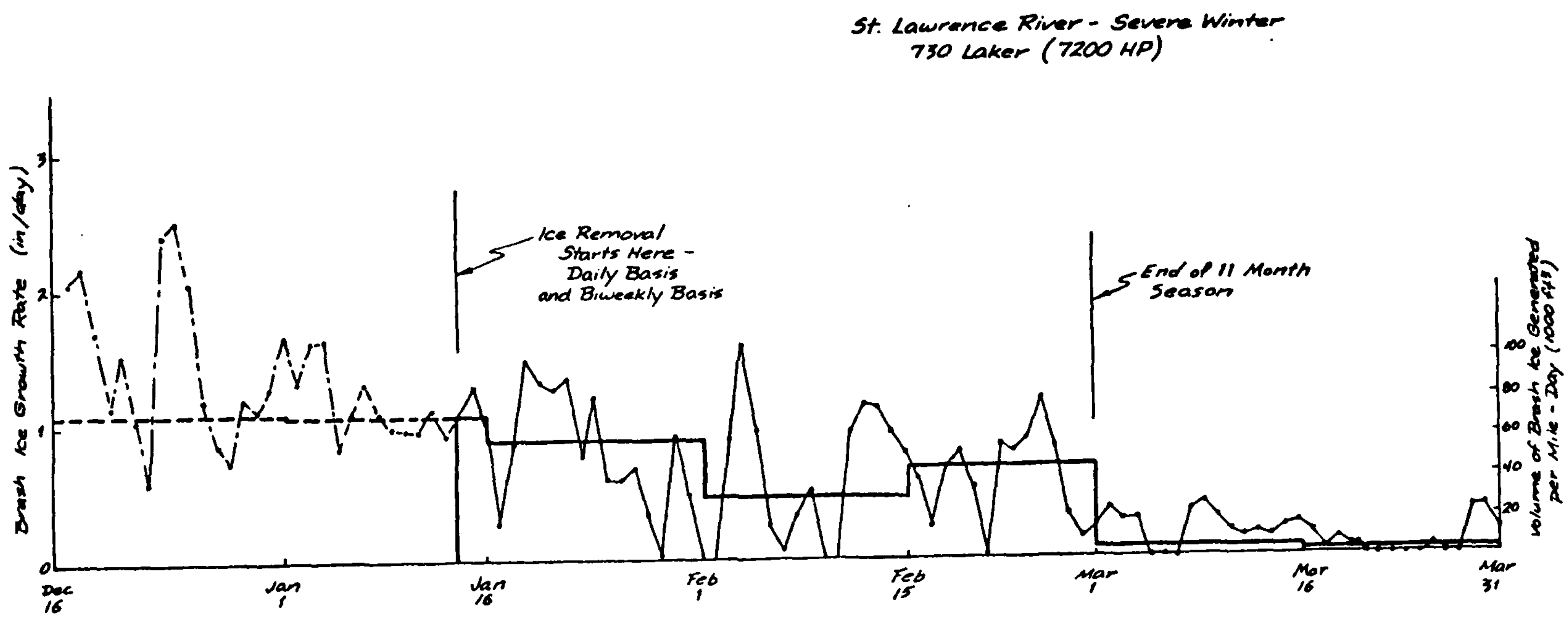
Brash Ice Removal Rate to Maintain Traffic in Turns
(Growth Rate = Removal Rate after 46 in. Ice Thickness is Reached)

Figure G.4.



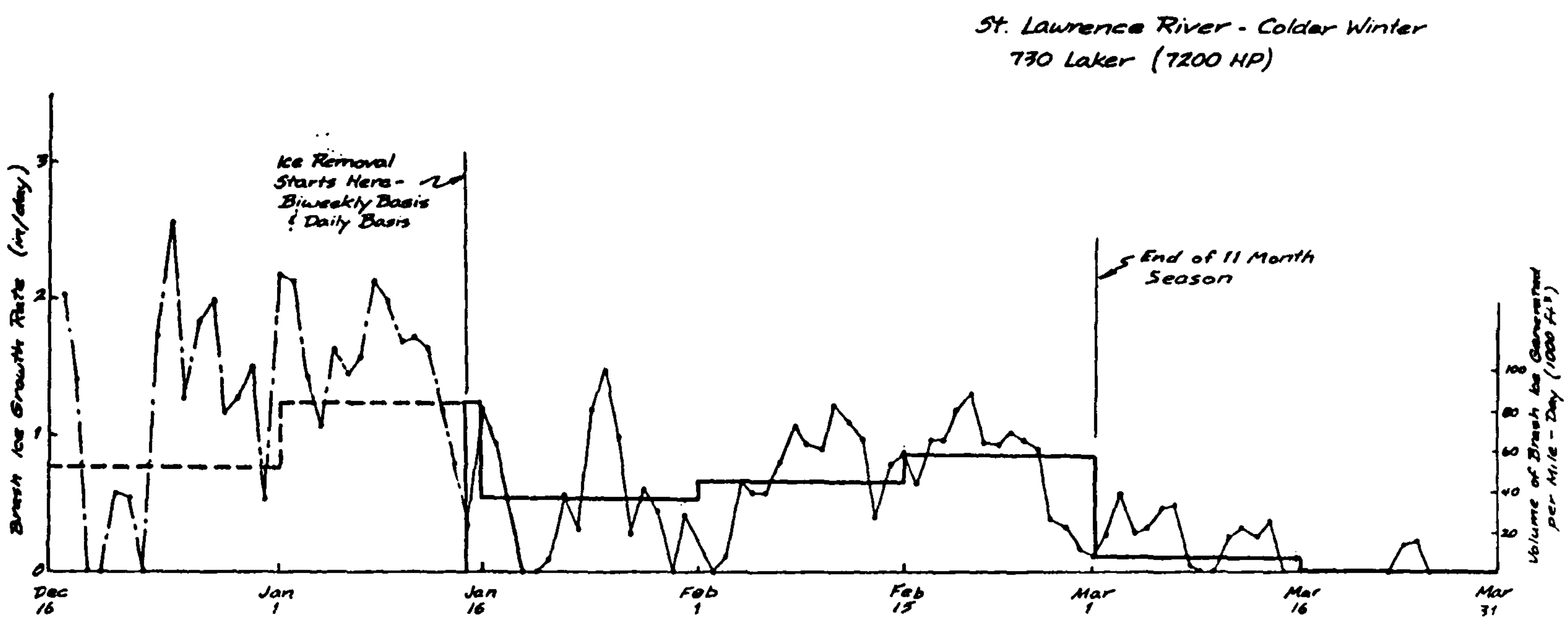
Brash Ice Removal Rate to Maintain Traffic in Turns
(Growth Rate = Removal Rate after 46 in. Ice Thickness is Reached)

Figure G.5.



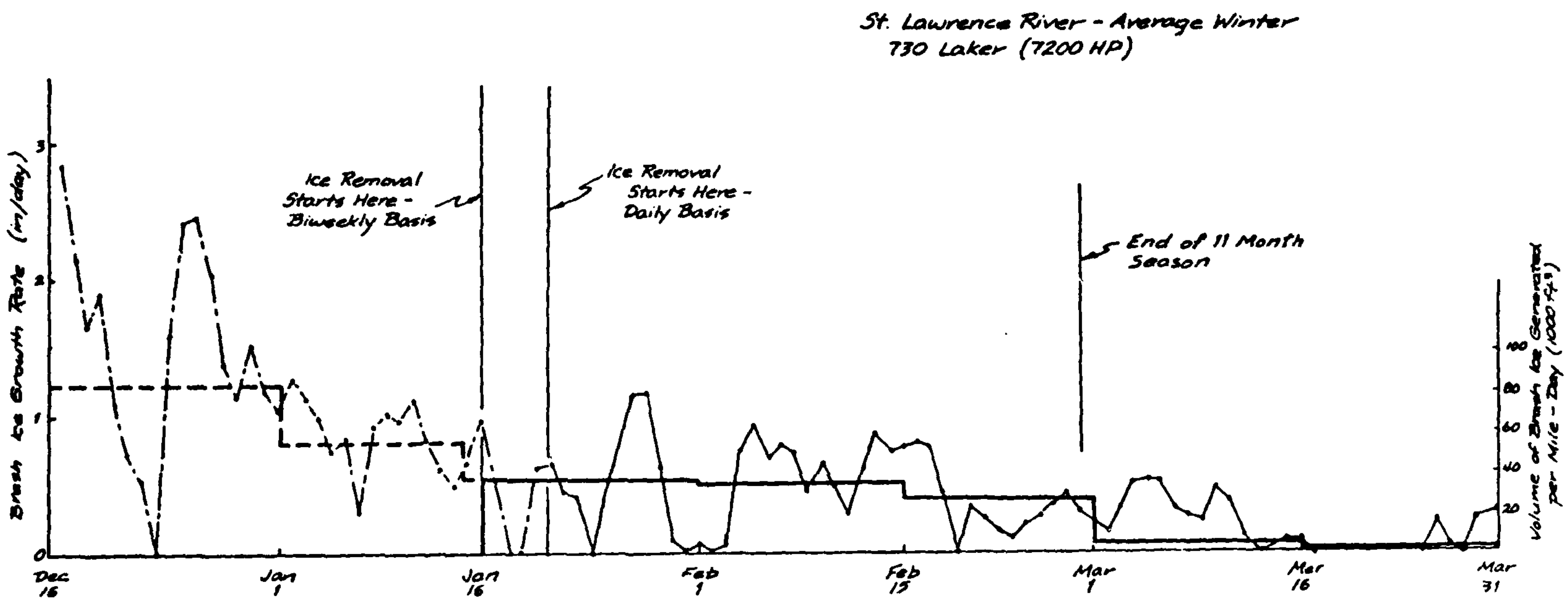
Brash Ice Removal Rate to Insure Maximum Delay of 9 Hours
(Growth Rate = Removal Rate after 9 Hr. Delay is Reached)

Figure G.6.



Brash Ice Removal Rate to Insure Maximum Delay of 9 Hours
(Growth Rate = Removal Rate after 9 Hr Delay is Reached)

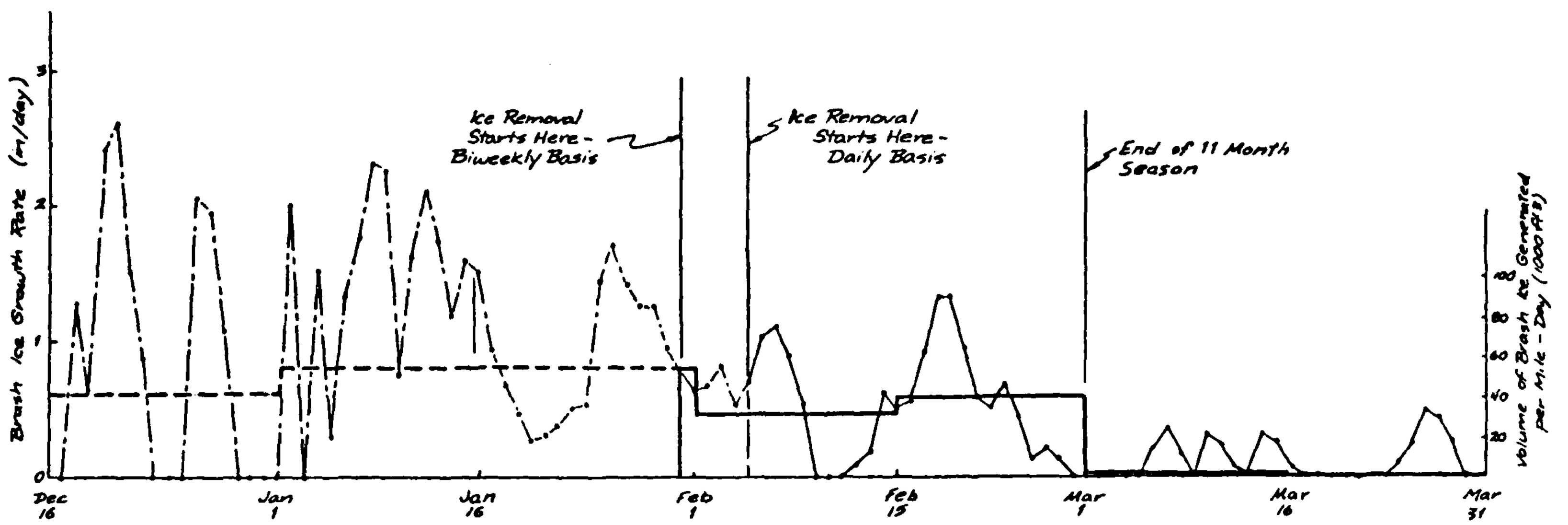
Figure G-7



Brash Ice Removal Rate to Insure Maximum Delay of 9 Hours
(Growth Rate = Removal Rate after 9 Hr Delay is Reached)

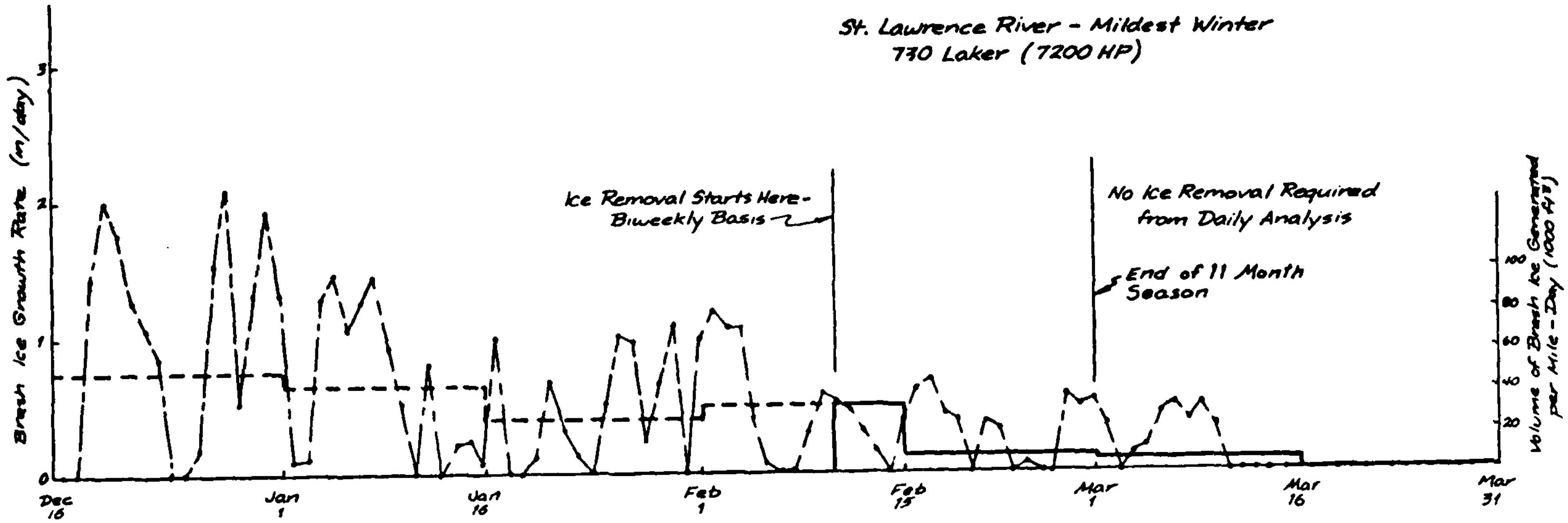
Figure G.8

St. Lawrence River - Milder Winter
730 Laker (7200 HP)



Brash Ice Removal Rate to Insure Maximum Delay of 9 Hours
(Growth Rate = Removal Rate after 9 Hr. Delay is Reached)

Figure G.9.



Brash Ice Removal Rate to Insure Maximum Delay of 9 Hours
(Growth Rate = Removal Rate after 9 Hr Delay is Reached)

Figure G.10

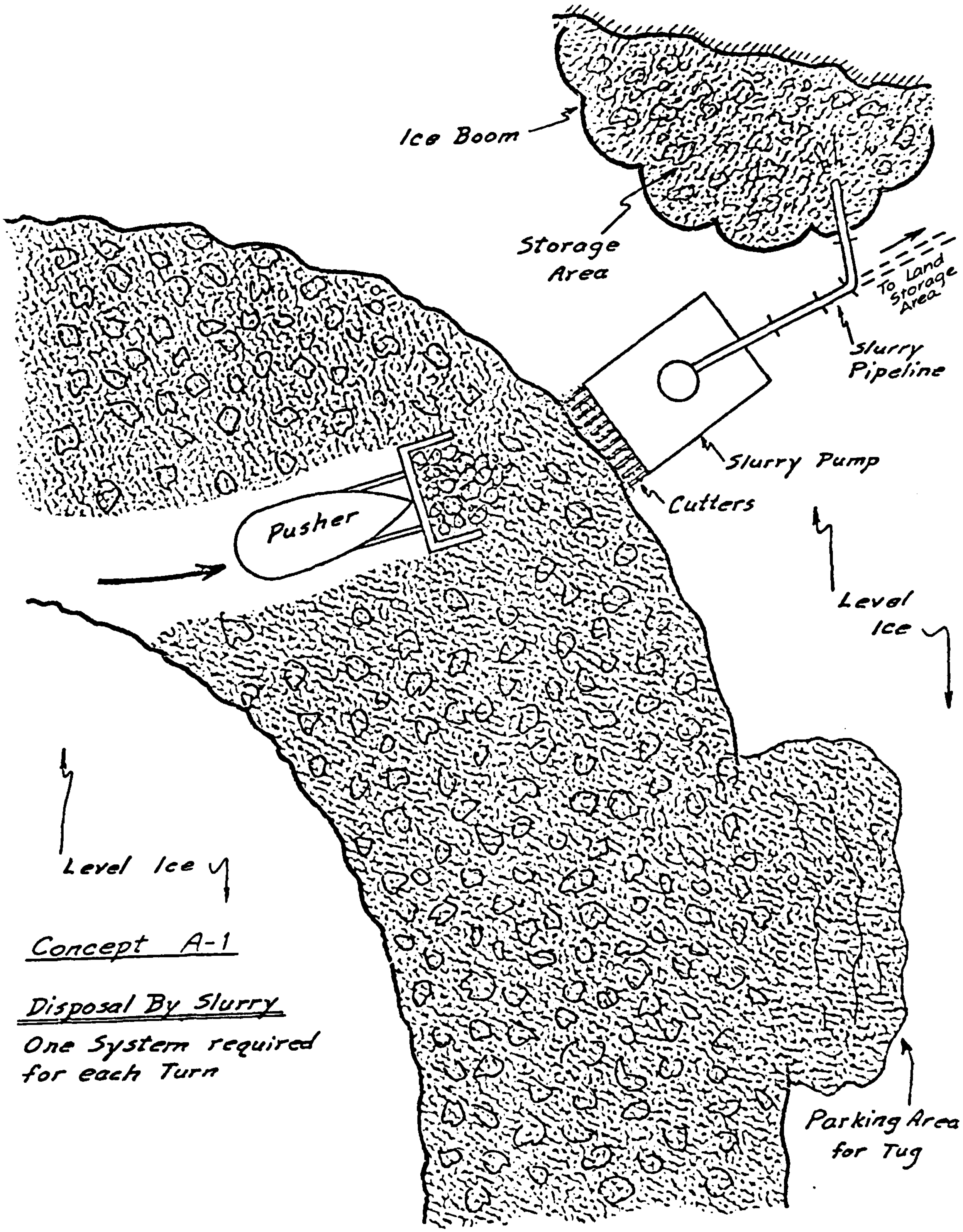
APPENDIX H

CHANNEL CLEARING CONCEPT SCREENING

DISPOSAL METHOD: Slurry (A.1)

CONCEPT DESCRIPTION: A marine craft pushes ice into a stationary ice cutter and collection platform. A slurry pump, blower, or conveyor (barge mounted) transfers brash ice to either a land based or water based storage area.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Pusher craft feeds ice pieces into saws, cutters, or grinders.	Possible problems with tugs or tractors combining shallow draft, high horesepower, and maneuverability within the channel must be resolved in the design. Shallow draft requirement not applicable in some areas.	Possible problems with tugs or tractors combining shallow draft, high horsepower, and maneuverability within the channel must be resolved in the design.
TRANSFER	Pumps and pipeline or conveyor on barge anchored outside of turn or channel.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	Storage area on land. Storage in boomed area just outside of channel	Storage on land appears feasible for Thousand Island, Brockville Narrows, Galop Island, Copeland Cut, Ogden Island Areas. Storage in boomed areas from B-O area and Carleton & Wolfe Island appears feasible.	Storage on land at Johnsons Point Turn and Striblings Point Turn would be in Canada Winter Point Turn is two miles from land. Possible problems with drainage. Possible problems with limited area close to Johnsons Point Turn and Mirre Pt Turn
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of a marine craft, barge-mounted ice cutter and transfer system, and a storage area.	In order to travel with the flow of traffic, many storage areas would need to be located along the length of the river.	Once storage areas have been designated, one system could be deployed near each Turn in the St. Marys River. There is generally no problem with accomplishing the daily ice removal within an 8-hour day.
CONCLUSION		Rejected. System does not move with the flow of traffic.	Accepted.



Concept A-1

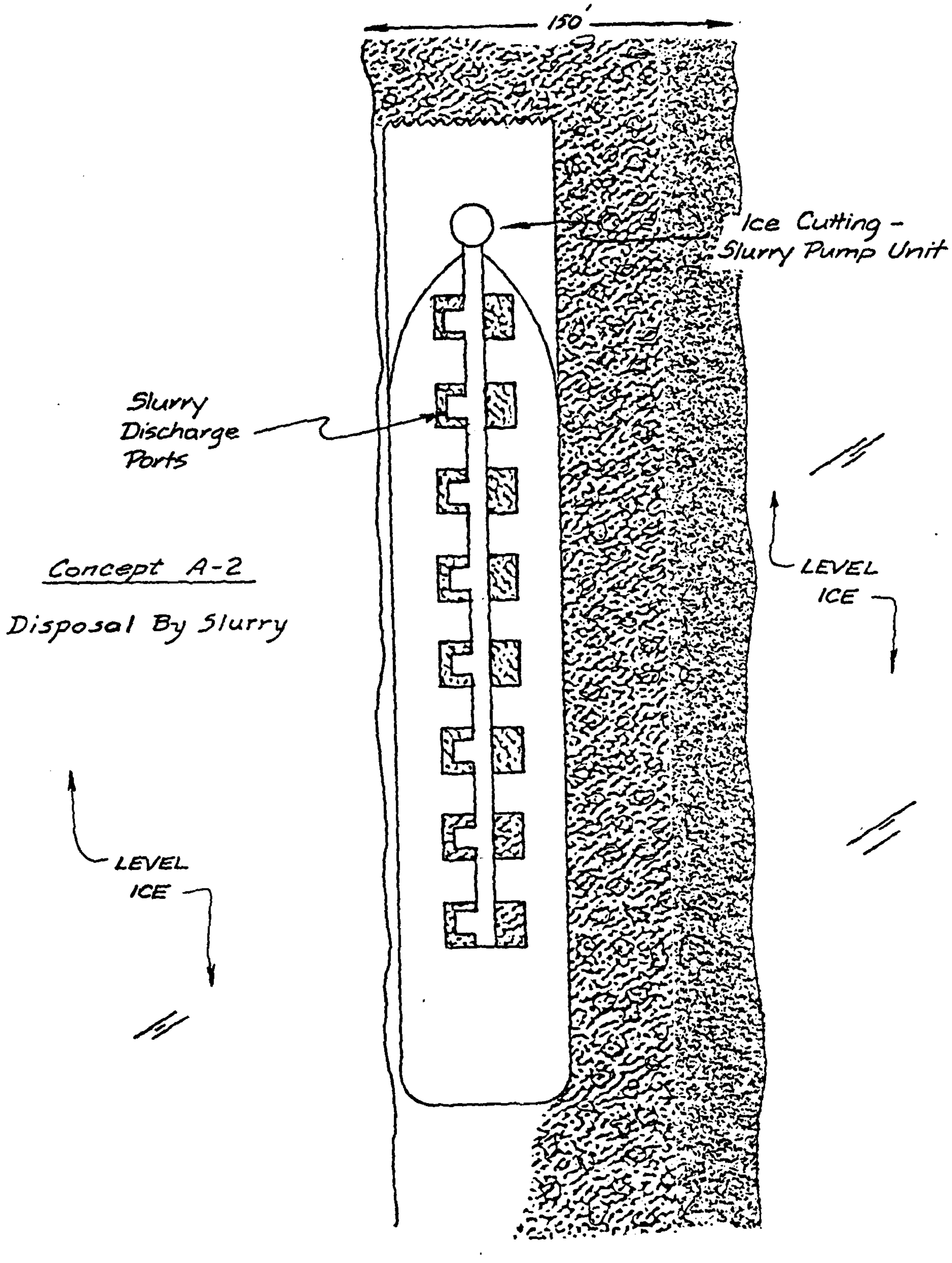
Disposal By Slurry

One System required for each Turn

DISPOSAL METHOD: Slurry (A.2)

CONCEPT DESCRIPTION: An ice cutter-slurry pump unit is mounted to the bow of a 730. The brash ice is stored in the ship and transported to a designated disposal area, either Lake Ontario or Lake Huron.

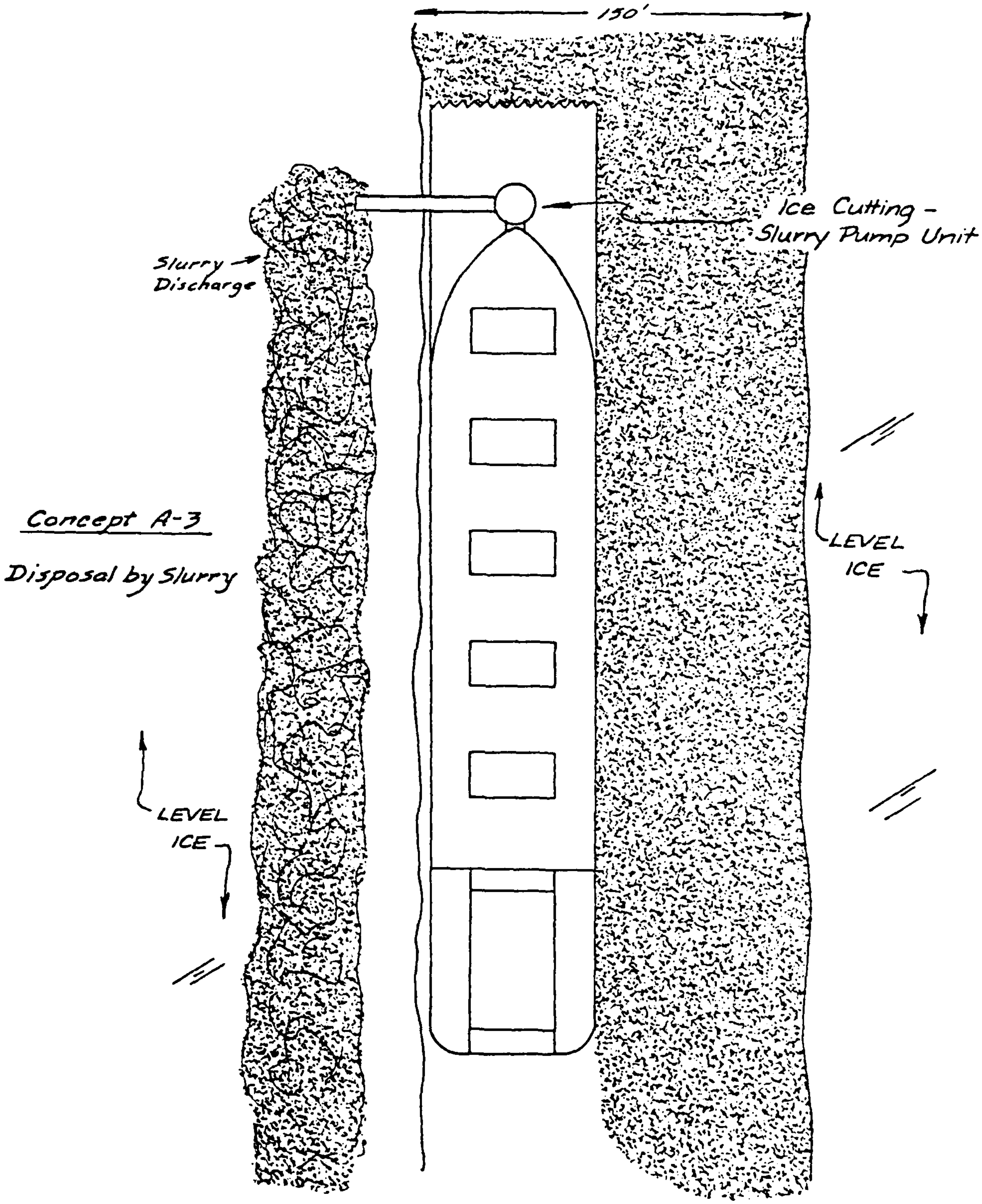
FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Forward movement of vessel drives ice into cutters, saws, or grinders	No foreseeable problems.	No foreseeable problems.
TRANSFER	Slurry pumps transfer brash ice to ship.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	Storage area is Lake Ontario for the St. Lawrence River. Storage area is Lake Huron for the St. Marys River	Lake Ontario is very deep. Brash ice would be dumped from stern of ship to mix with the already broken ship channel ice. Brash ice would be dumped away from normal shipping lanes. No foreseeable problems.	Lake Huron is deep enough to handle brash ice volume. Brash ice would be dumped from stern of ship to mix with the already broken ship channel ice. Brash ice would be dumped away from normal shipping lanes. No foreseeable problems.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of a ice cutter and slurry pump unit attached to the bow of a 730.	The 730 could be deployed on a mission basis traveling with the flow of traffic. This system operates continuously. The bow unit could be easily stowed between work periods.	The 730 may require additional power to negotiate the brash infested Turns of the St. Marys River. The bow unit could easily be stowed between work periods.
CONCLUSION		Accepted.	Accepted.


150'
Ice Cutting - Slurry Pump Unit
Slurry Discharge Ports
Concept A-2
Disposal By Slurry
LEVEL ICE
LEVEL ICE

DISPOSAL METHOD: Slurry (A.3)

CONCEPT DESCRIPTION: A slurry pump mounted on a marine craft transfers brash ice to top of solid ice cover via ejector, conveyor, or pipeline.

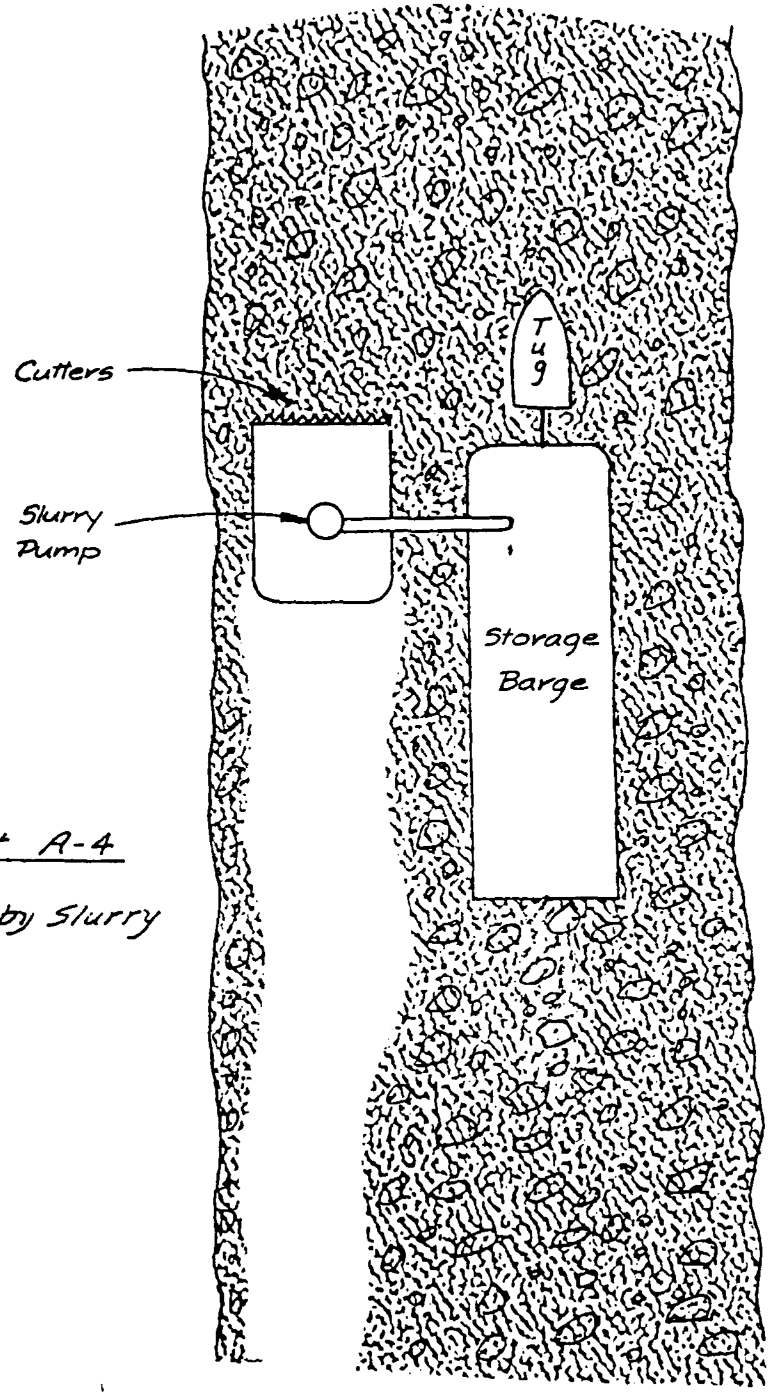
FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Slurry pump and pipeline on board vessel.	Possible problems with tugs or tractors combining shallow draft, high horespower and maneuverability within the channel must be resolved in the design. Shallow draft requirement not applicable in some areas.	Possible problems with tugs or tractors combining shallow draft, high horsepower and maneuverability within the channel must be resolved in the design.
TRANSFER	Slurry pump and pipeline, ejector, conveyor on board vessel.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operatin and between operating shifts must be resolved in the design.
STORAGE	Ice stored on top of unbroken ice cover.	The unbroken ice cover should remain intact when brash ice is dumped on top. Method for spreading brash ice on top of ice cover needs to be determined.	Adequate storage at the turns in the St. Marys River is not available. It is feared that the thickened ice sheet may break off and become a hazard to navi-gation.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system concists of ice cutter and slurry pump and either ejector, conveyor, or pipeline mounted on marine craft.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Accepted.	Rejected. Ice cover cannot support required ice storage.


150'
Ice Cutting -
Slurry Pump Unit
Slurry
Discharge
Concept A-3
Disposal by Slurry
LEVEL
ICE
LEVEL
ICE

DISPOSAL METHOD: Slurry (A.4)

CONCEPT DESCRIPTION: A marine craft fitted with an ice cutter and slurry pump would recover the brash ice. The brash ice would be temporarily stored in a barge. The barge would be towed to an area where the brash ice would be stored.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Pusher craft feeds ice pieces into saws, cutters, or grinders.	Possible problems with tugs or tractors combining shallow draft, high horsepower, and maneuverability within the channel must be resolved in the design. Shallow draft requirement not applicable in some areas.	Possible problems with tugs or tractors combining shallow draft, high horesepower, and maneuverability within the channel must be resolved in the design. Shallow draft requirement not applicable in some areas.
TRANSFER	Slurry pump transfers ice to barge. Barge is then towed to dumping site.	Size and power requirements of towing tug must be resolved in the design.	Size and power requirements of towing tug must be resolved in the design.
STORAGE	Brash ice stored on land or in water (river or lake).	Brash ice could be stored in Lake Ontario or deep river ice boom areas. If land is nearby, storage on land appears feasible.	Brash ice could be stored in Lake Huron. It could also be stored on Neebish or Sugar Island.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of a slurry pump and ice cutter and a storage barge and tow boat.	This system could be deployed on a mission basis. A number of barges may be required to carry out brash ice removal on a continuous basis.	No foreseeable problems.
CONCLUSION		Accepted.	Accepted.



Concept A-4

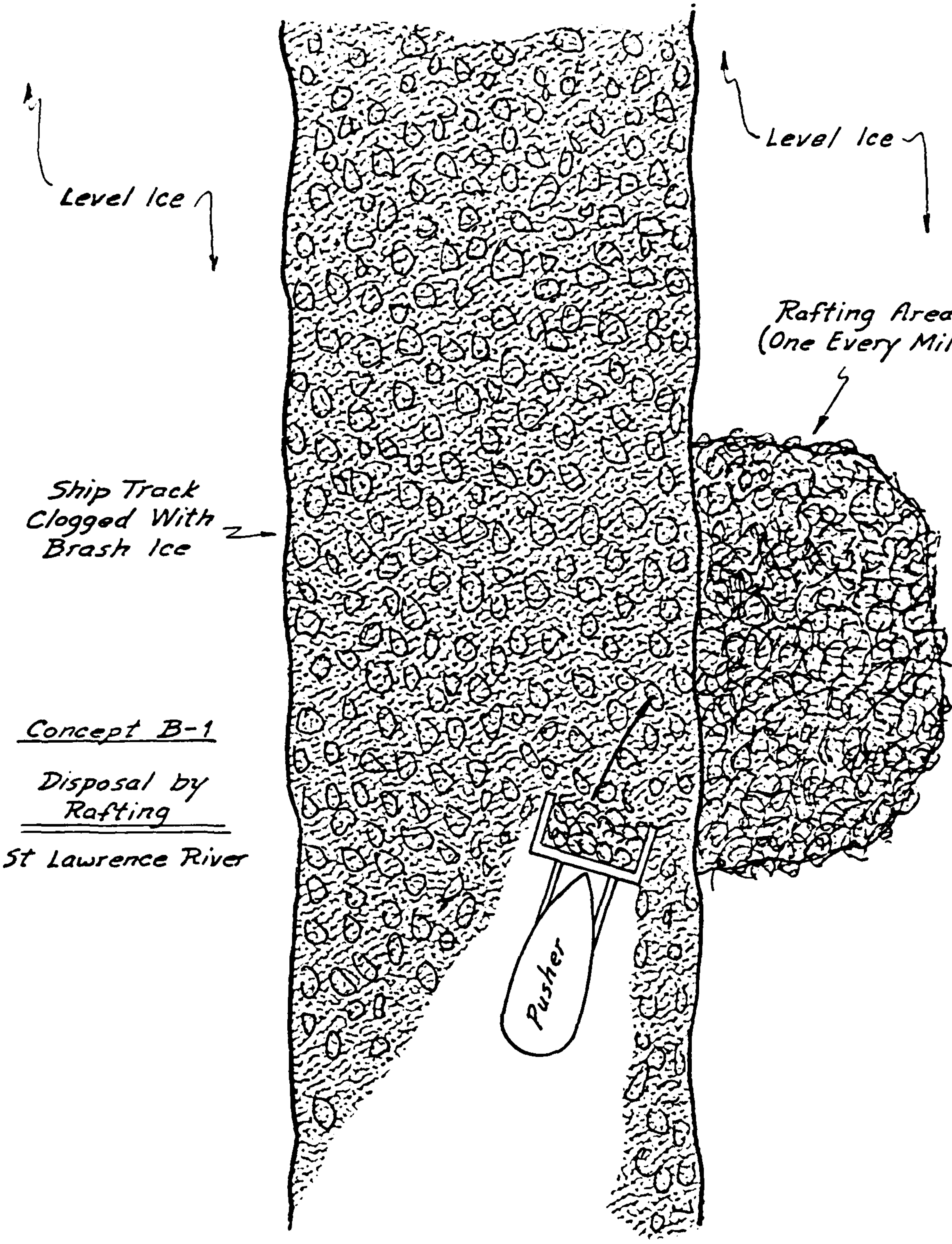
Disposal by Slurry

DISPOSAL METHOD: Rafting (B.1)

CONCEPT DESCRIPTION: High powered tug or AST (Archimedean Screw Tractor) pushes brash ice into storage area.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Vessel would break ice and then raft broken and brash ice into storage area.	No foreseeable problems.	No foreseeable problems.
RECOVERY	Vessel must remove brash ice at the required rates.	High powered, shallow draft*, maneuverable vessel required. Recovery is not continuous. Time would be lost maneuvering the vessel during rafting process.	High powered, shallow draft, maneuverable vessel required. Recovery is not continuous. Time would be lost maneuvering the vessel during rafting process.
TRANSFER	Vessel pushes brash ice to storage location.	Rafting process may interfere with local ship traffic.	Rafting process may interfere with local ship traffic.
STORAGE	Storage area in water but out of the channel.	Adequate storage may not be available at some locations in St. Lawrence River.	Adequate storage in the shallow water areas outside the Turns in the St. Marys River is available.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The sytem consists of a high powered tug or AST and a storage area.	In order to travel with the flow of traffic, many storage areas would need to be located along the length of the International Section.	Once storage areas have been designated, one system could be deployed near each Turn in the St. Marys River. There is no problem with accomplishing the daily ice removal within an 8-hour work day.
CONCLUSION		Rejected. This system would not move with the flow of traffic.	Accepted.

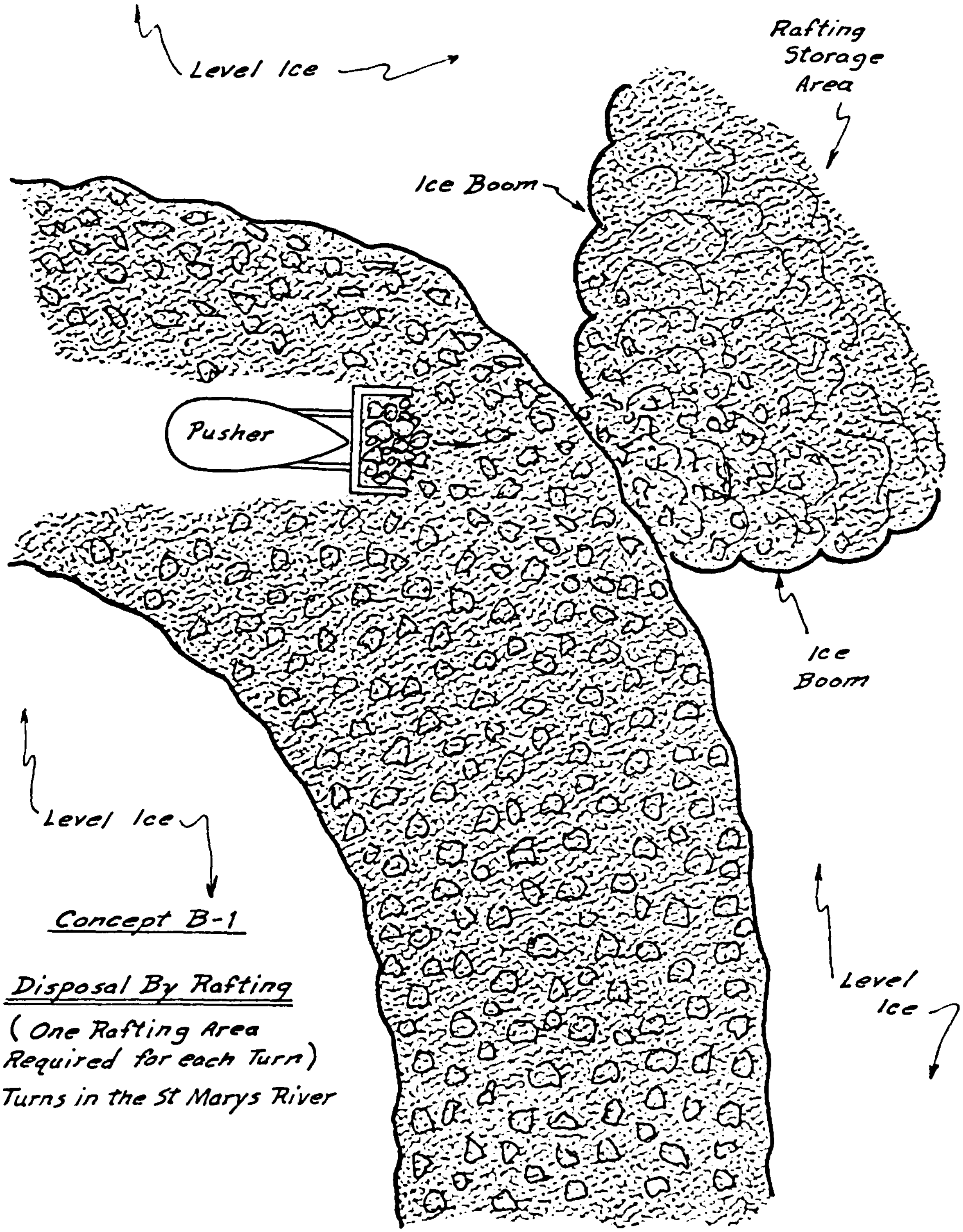
* Not a requirement for some areas of St. Lawrence River.



Concept B-1

Disposal by Rafting

St Lawrence River



Concept B-1

Disposal By Rafting

(One Rafting Area Required for each Turn)

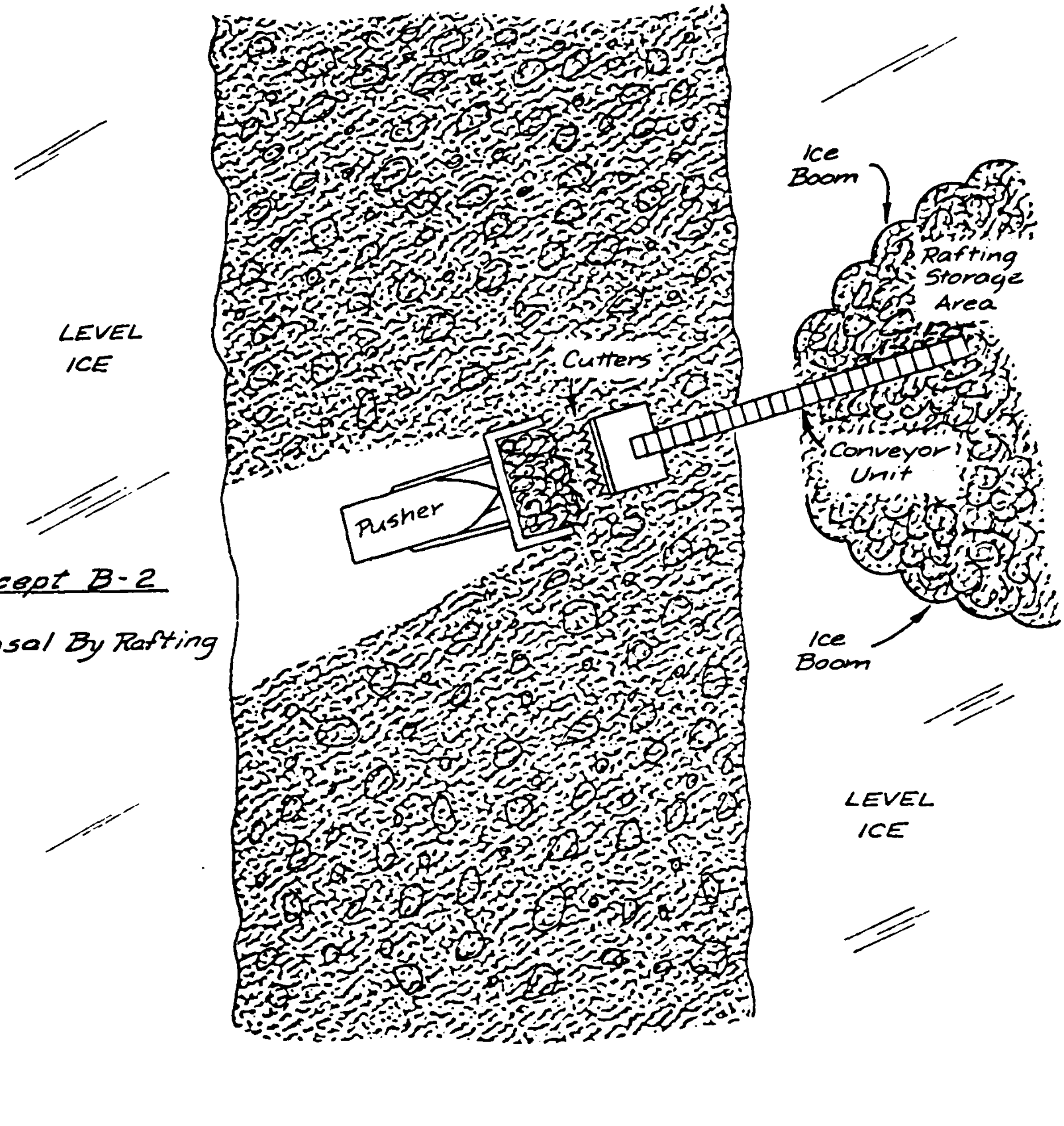
Turns in the St Marys River

DISPOSAL METHOD: Rafting (B.2)

CONCEPT DESCRIPTION: Self-contained conveyor belt unit transfers brash ice to storage area.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Tug, tractors, dragline feed ice into cutter and then into conveyor belt unit.	High powered, shallow draft*, maneuverable vessel required. Recovery is not continuous. Time would be lost maneuvering the vessel during rafting process.	High powered, shallow draft, maneuverable vessel required. Recovery is not continuous. Time would be lost maneuvering the vessel during rafting process.
TRANSFER	Conveyor belt transfers ice to storage area.	Possible icing problems during operation and between shifts must be resolved in the design.	Possible icing problems during operation and between shifts must be resolved in the design.
STORAGE	Storage area in water but out of the channel.	Adequate storage may not be available at some locations in St. Lawrence River.	Adequate storage in the shallow water areas outside the Turns in the St. Marys River is available.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of tug, tractors, drag line feed into ice cuter and conveyor belt.	This sytem would be required to stop to transfer ice to the storage area. Hence this system does not travel with the flow of traffic.	No foreseeable problems.
CONCLUSION		Rejected. This system does not move with the flow of traffic.	Accepted.

* Not a requirement for some areas of St. Lawrence River.



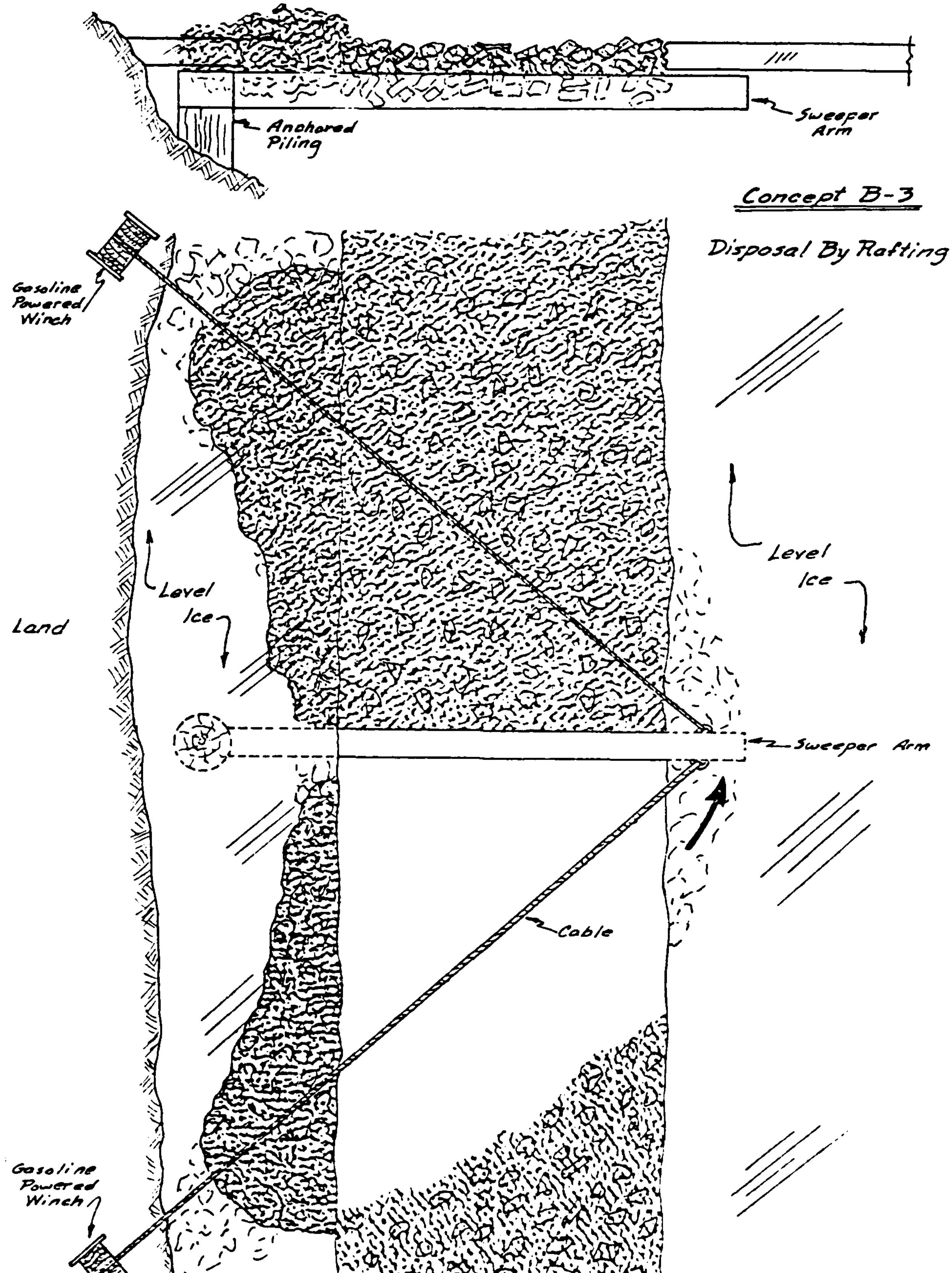
Concept B-2

Disposal By Rafting

DISPOSAL METHOD: Rafting (B.3)

CONCEPT DESCRIPTION: A rectangular sweeper arm removes brash ice from channel.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	A sweeper arm would move across the brash ice infested channel and break the ice as it moved.	Possible icing and icebreaking problems must be resolved in the design.	Possible icing and icebreaking problems must be resolved in the design.
RECOVERY	The sweeper must be able to remove brash ice at the specified rates.	Anchoring sweeper arm in deep waters may be a problem.	Anchoring sweeper arm in 4 Turns of St. Marys River seems to be feasible.
TRANSFER	Sweeper arm moves brash ice out of channel.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	Storage would be in fixed areas in the rivers.	Adequate storage may not be available at some locations in the St. Lawrence River.	Adequate storage at the Turns in the St. Marys River may not be available due to localized nature of storage area.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of a rectangular sweeper arm.	Many of these systems would be required for the St. Lawrence River. This system may be a hazard to navigation.	This system may be a hazard to navigation.
CONCLUSION		Rejected. Storage may not be sufficient in immediate vicinity of sweeper arm. System does not move with flow of traffic. System is a hazard to navigation.	Rejected. Storage of brash ice at Turns in St. Marys River may disrupt hydraulic regime of the river. This system would be a hazard to navigation.


Anchored Piling
Sweeper Arm
Concept B-3
Disposal By Rafting
Gasoline Powered Winch
Level Ice
Level Ice
Land
Sweeper Arm
Cable
Gasoline Powered Winch

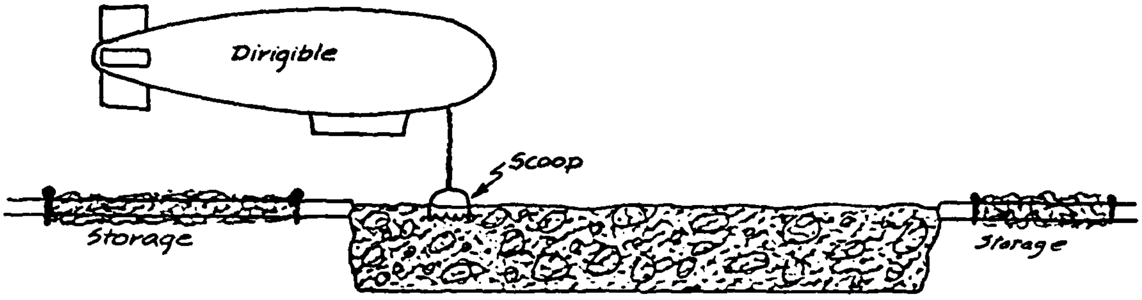
DISPOSAL METHOD: Rafting (B.4)

CONCEPT DESCRIPTION: A dirigible scoops up brash ice and deposits in storage area.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	The scooper would break the ice.	Possible icing problems with scooper would need to be resolved in the design.	Possible icing problems with scooper would need to be resolved in the design.
RECOVERY	The scooper would remove the brash ice at the required rates.	Size of scooper and dirigible would need to be determined.	Size of scooper and dirigible would need to be determined.
TRANSFER	The dirigible would transit to the storage area.	High winds and cold environment may effect dirigible operations.	High winds and cold environment may effect dirigible operations.
STORAGE	Storage could be on land or river.	Adequate storage may not be available at some locations in the St. Lawrence River. Storage on land seems feasible.	Adequate storage near Turns of St. Marys River is available. Storage on land seems feasible.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consits of a scoop attached to a dirigible and a brash ice storage area.	Special training for dirigible operation is required. Maintenance of dirigible may also require specialized training.	Special training for dirigible operation is required. Maintenance of dirigible may also require specialized training.
CONCLUSION		Rejected. Special equipment and training required for this system; therefore, logistic requirement not met.	Rejected. Special equipment and training required for this system; therefore, logistic requirement not met.

Concept B-4

Disposal By Rafting

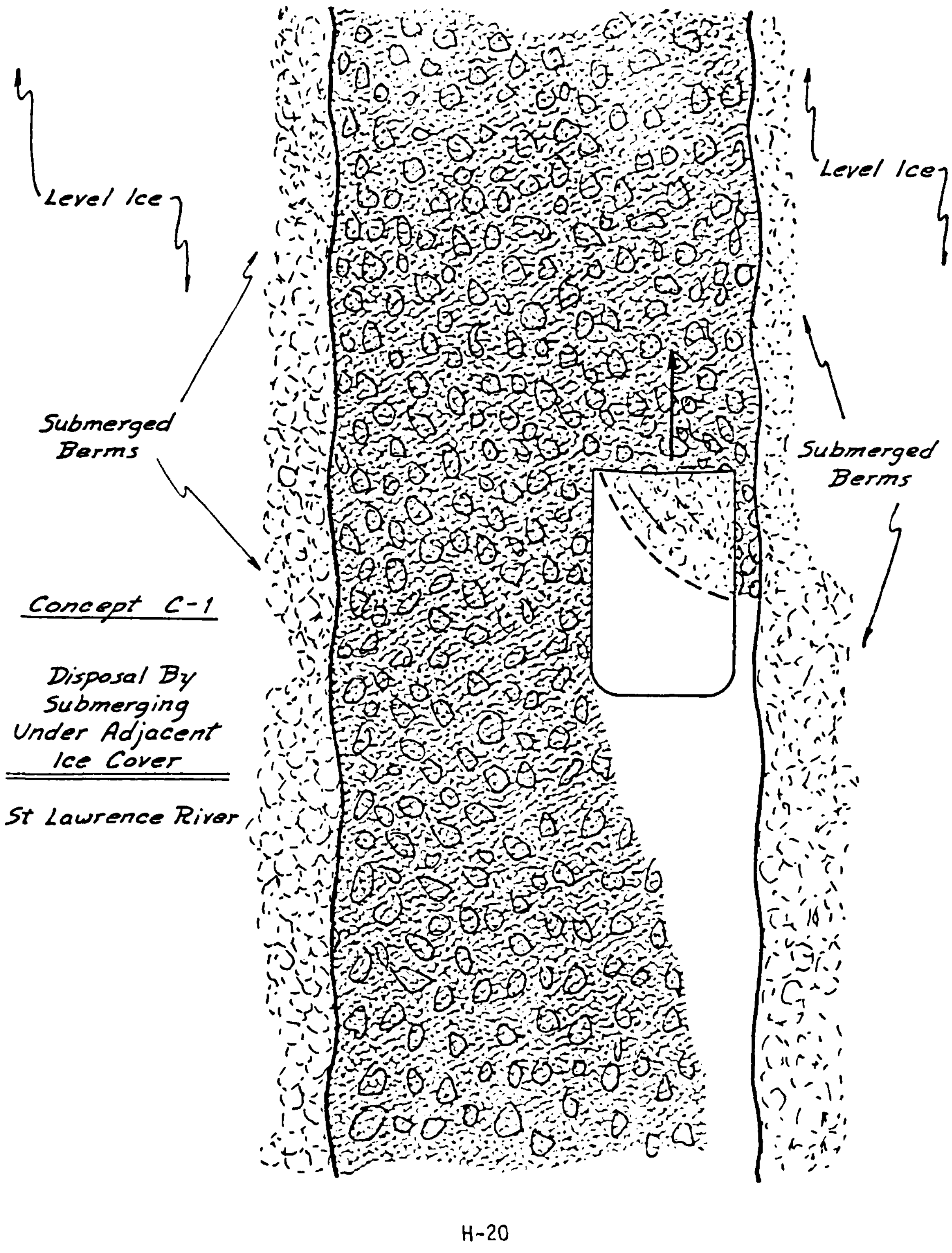


Note:
Dirigible Drags Brash
Ice in Both Directions

DISPOSAL METHOD: Displacement Under Ice (C.1)

CONCEPT DESCRIPTION: Ship mounted single or double diverter (bow mounted or pulled at the stern) pushes brash ice underneath solid ice cover

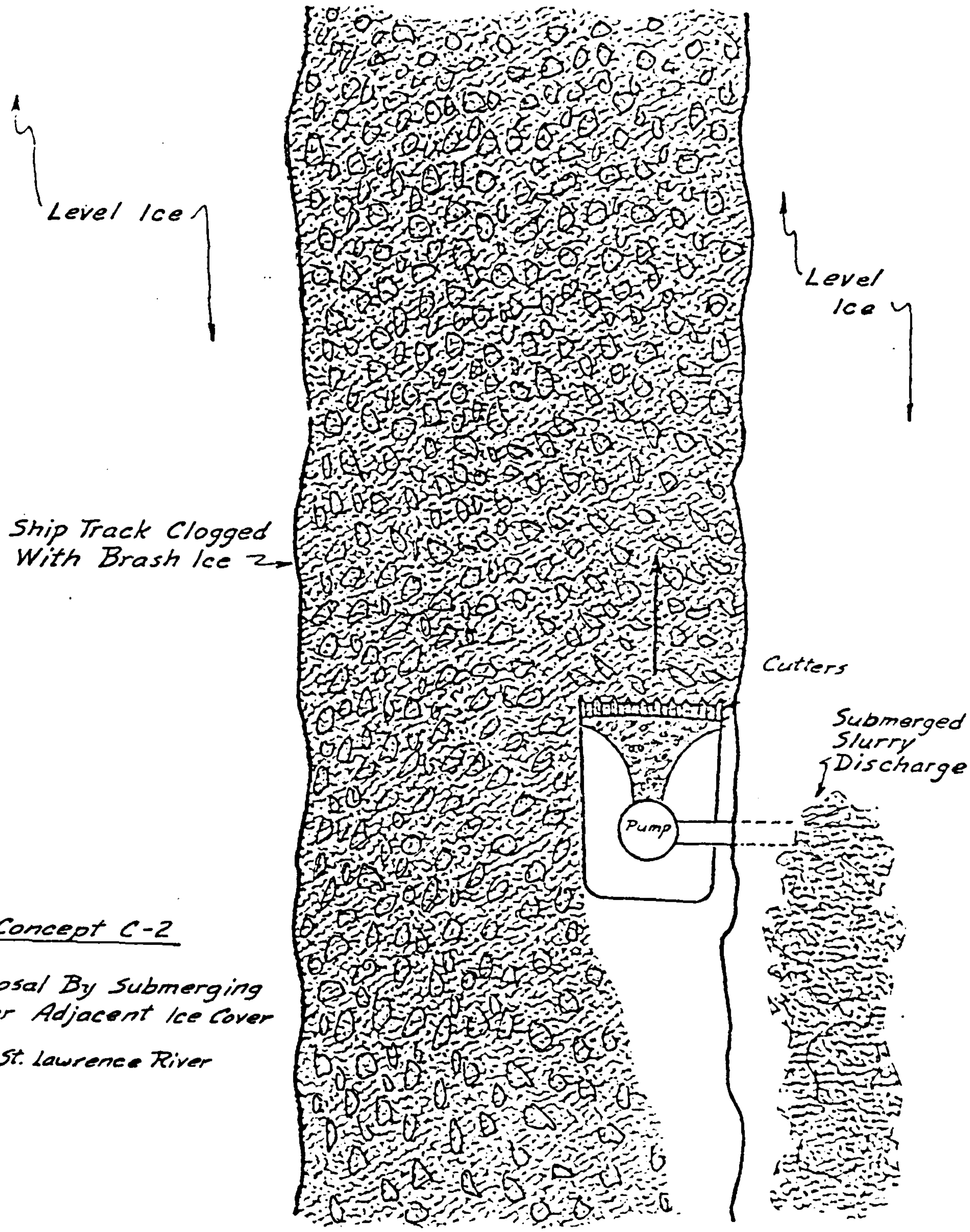
FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Ice should be broken by bow of craft.	Icebreaking problems must be resolved in the design.	Icebreaking problems must be resolved in the design.
RECOVERY	Ice would be pushed under ice at the required rates using the diverter.	Size and shape of the diverter would determine recovery rate. Side forces would require side thrusters.	Size and shape of the diverter would determine recovery rate. Side forces would require side thrusters.
TRANSFER	Ice would be pushed under the ice at the required rates.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	Storage would be under the ice.	Possible problems in restricted channels subject to ship-induced drawdown and surge and in currents where ice pieces return to ship channel.	Possible problems in restricted channels subject to ship-induced drawdown and surge and in currents where ice pieces return to ship channel.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of a single or double diverter mounted to a ship or a barge.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Storage method may not be feasible.	Rejected. Storage method may not be feasible.


Level Ice
Level Ice
Submerged Berms
Submerged Berms
Concept C-1
Disposal By Submerging Under Adjacent Ice Cover
St Lawrence River

DISPOSAL METHOD: Displacement Under Ice (C.2)

CONCEPT DESCRIPTION: A slurry pump would shoot brash ice under ice cover.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Slurry pump and pipeline on board vessel.	Possible problems with tugs or tractors combining shallow draft, high horsepower and maneuverability within the channel must be resolved in the design. Shallow draft requirement not applicable in some areas.	Possible problems with tugs or tractors combining shallow draft, high horsepower and maneuverability within the channel must be resolved in the design.
TRANSFER	Slurry pump and under water nozzle would be used to "shoot" brash ice under ice cover.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	Ice would be stored under ice cover.	Possible problems in restricted channels subject to ship-induced drawdown and surge and in currents where ice pieces return to ship channel.	Possible problems in restricted channels subject to ship-induced drawdown and surge and in currents where ice pieces return to ship channel.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of an ice cutter and a slurry pump that would shoot brash ice under the ice.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Storage method may not be feasible.	Rejected. Storage method may not be feasible.



Concept C-2

Disposal By Submerging Under Adjacent Ice Cover

St. Lawrence River

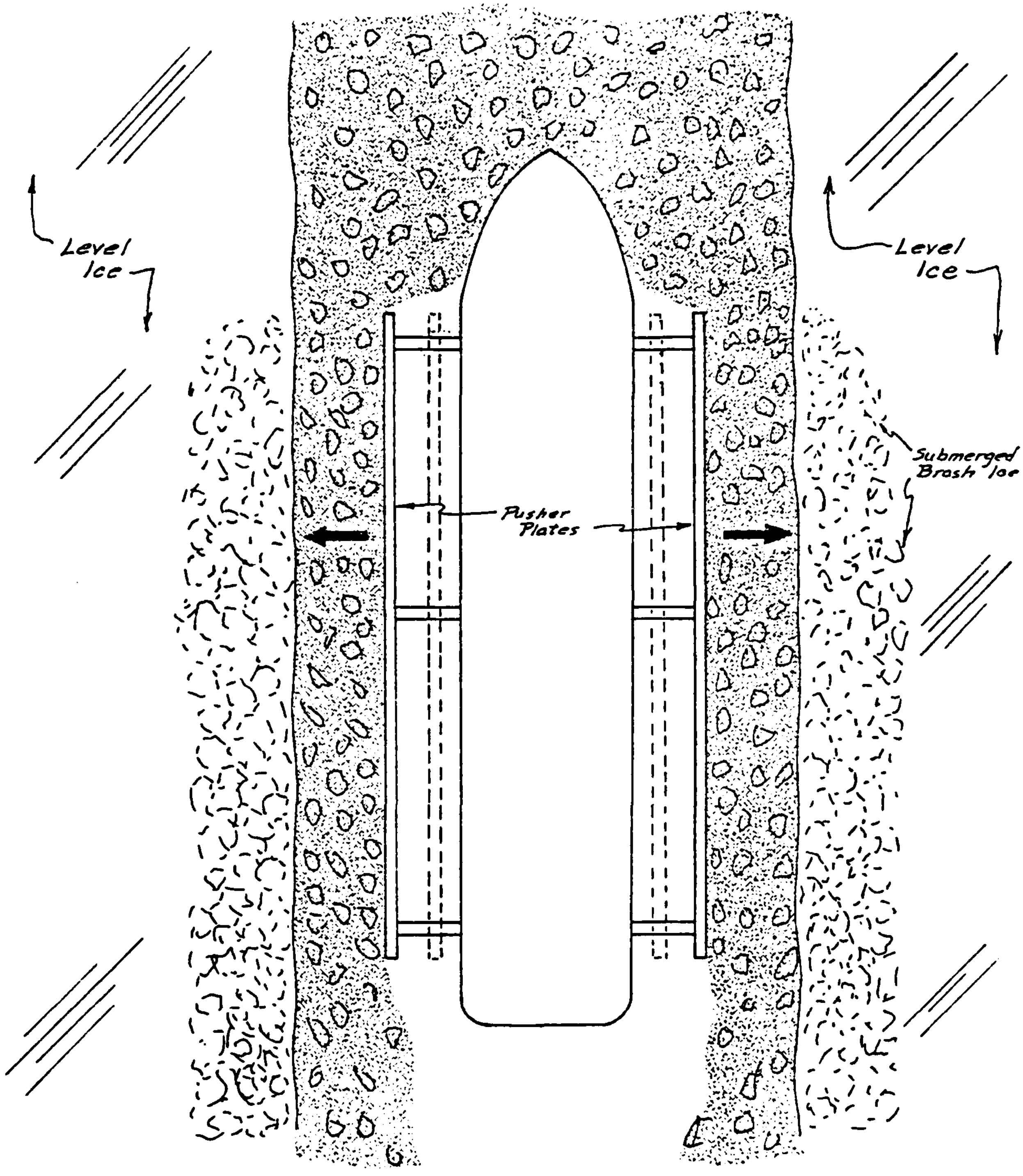
DISPOSAL METHOD: Displacement Under Ice (C.3)

CONCEPT DESCRIPTION: *Pusher plates attached to side of ship would move brash ice under ice cover.*

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Pusher plates would be mounted with sloping sides to break ice in the flexural mode.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	The plates would push the brash ice at the required rates.	Mechanical design problems must be resolved.	Mechanical design problems must be resolved.
TRANSFER	Plates push ice to storage area under ice at the required rates.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	The brash ice would be stored under the ice.	Possible problems in restricted channels subject to ship-induced drawdown and surge and in currents where ice pieces return to ship channel.	Possible problems in restricted channels subject to ship-induced drawdown and surge and in currents where ice pieces return to ship channel.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of pusher plates attached to side of ship.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Storage method may not be feasible.	Rejected. Storage method may not be feasible.

Concept C-3

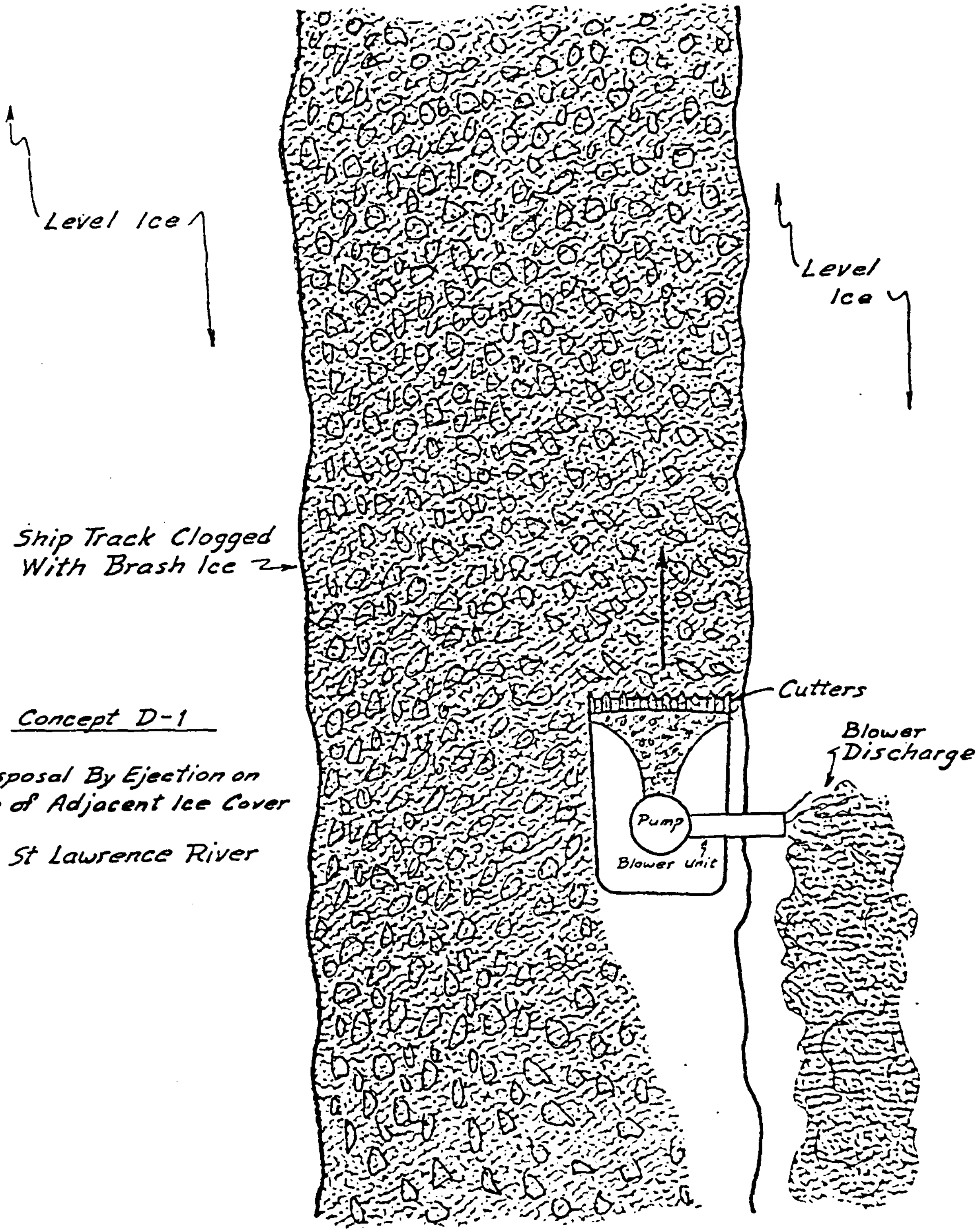
Disposal By Submerging Under Adjacent Ice Cover



DISPOSAL METHOD: Ejection on Top of Ice (D.1)

CONCEPT DESCRIPTION: A ship mounted conveyor belt, slurry pump, or brash ice blower device would be used to transfer brash ice from the channel to the top of the ice.

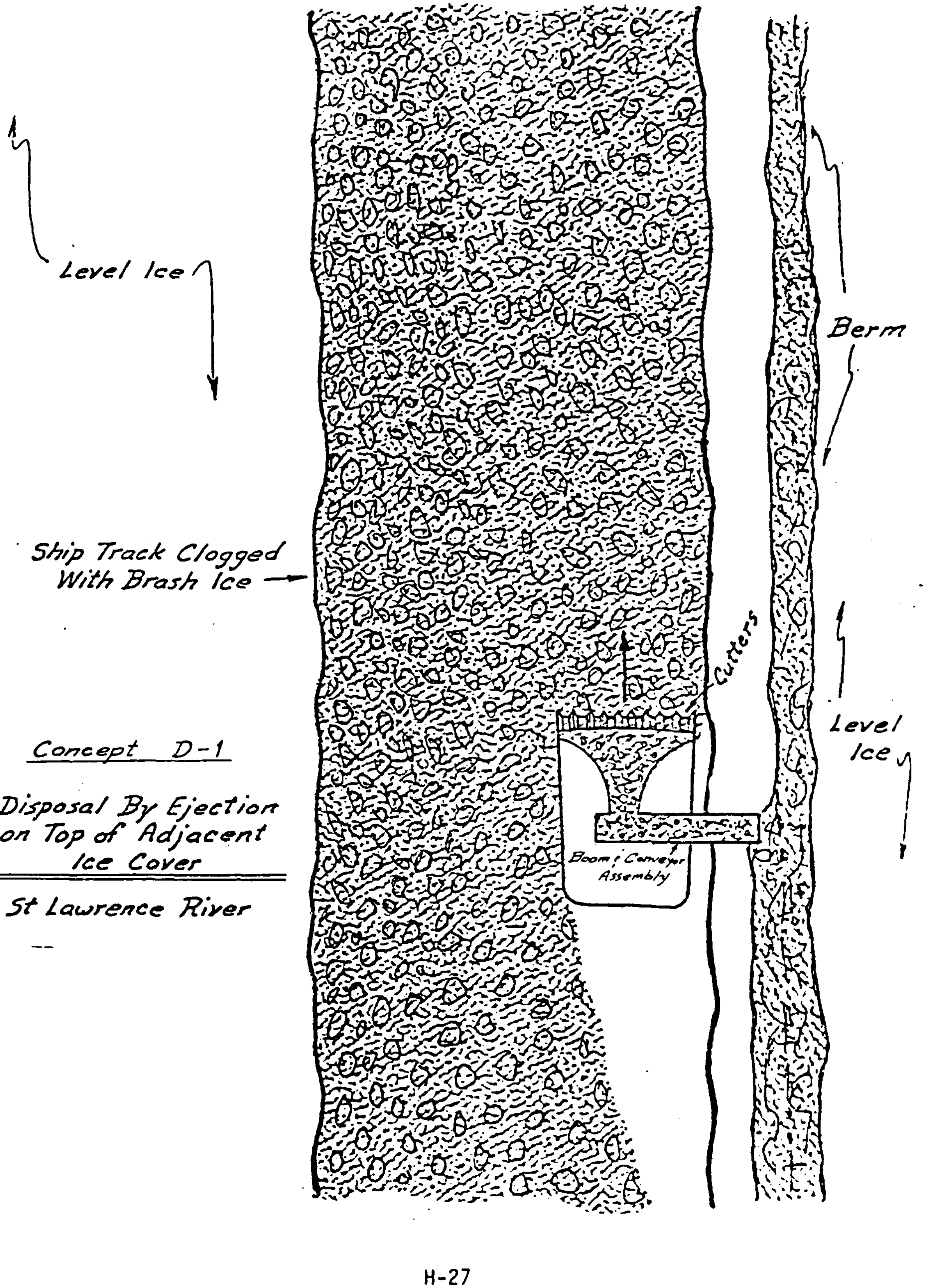
FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible ice problems which must be resolved in the design.	Possible ice problems which must be resolved in the design.
RECOVERY	Broken ice would be fed into conveyor belt, slurry pump, or brash ice blower device.	Possible icing problems which must be resolved in design.	Possible icing problems which must resolved in design.
TRANSFER	Ice would be transferred to top of ice via conveyor belt, slurry pump, or brash ice blower device.	Accumulated brash ice on top of ice cover may cause problems during spring breakup.	Accumulated brash ice on top of ice cover may cause problems during spring breakup.
STORAGE	Storage on top of ice sheet.	Possible icing problems during operation and between operating shifts must be resolved in the design	Possible icing problems during operation and between operating shifts must be resolved in the design.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of a ship mounted ice cutter, conveyor belt, slurry pump, or brash ice blower.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Accepted.	Rejected. Ice cover cannot support required ice storage.



Concept D-1

Disposal By Ejection on Top of Adjacent Ice Cover

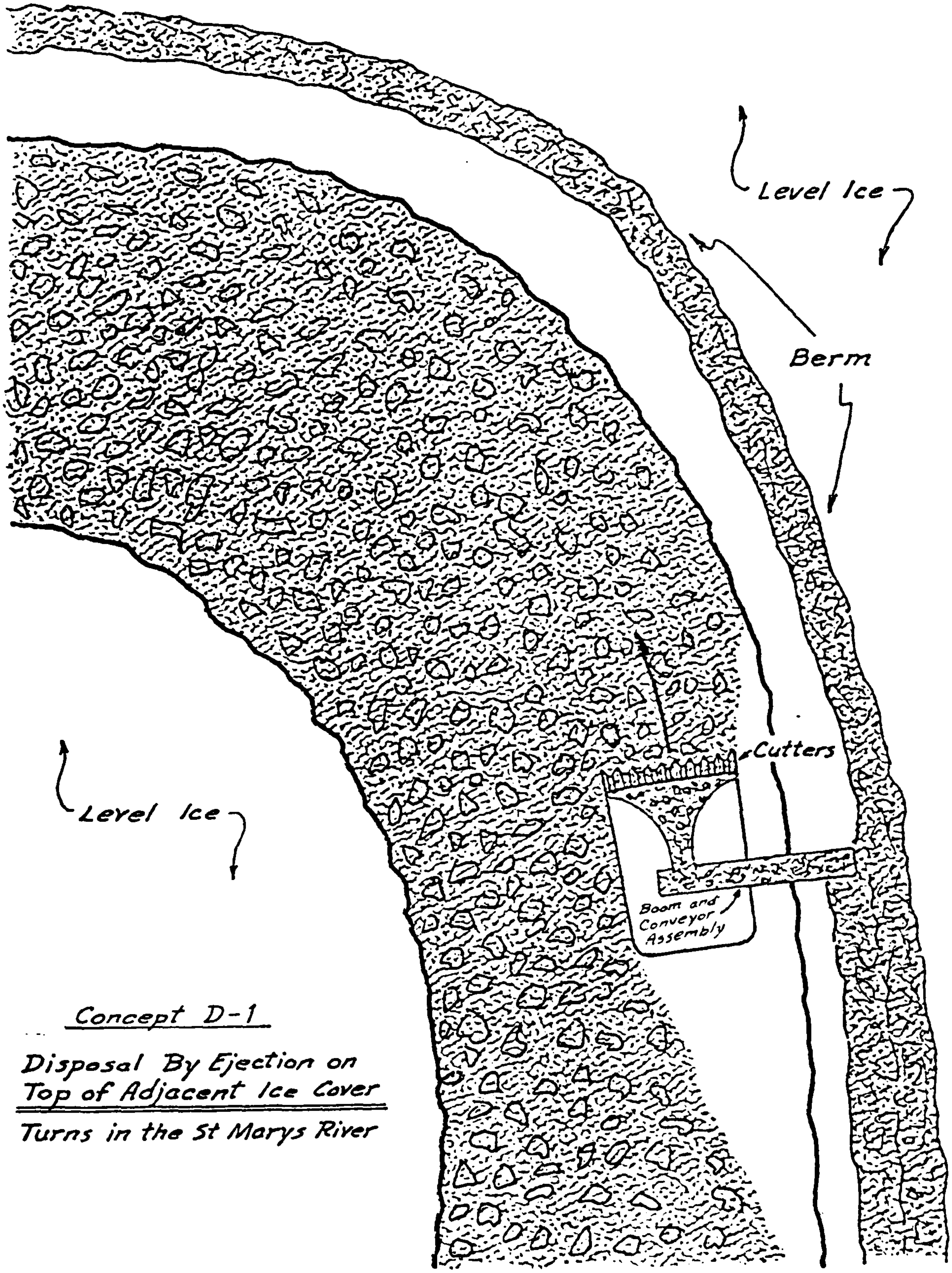
St Lawrence River



Concept D-1

Disposal By Ejection on Top of Adjacent Ice Cover

St Lawrence River



Concept D-1

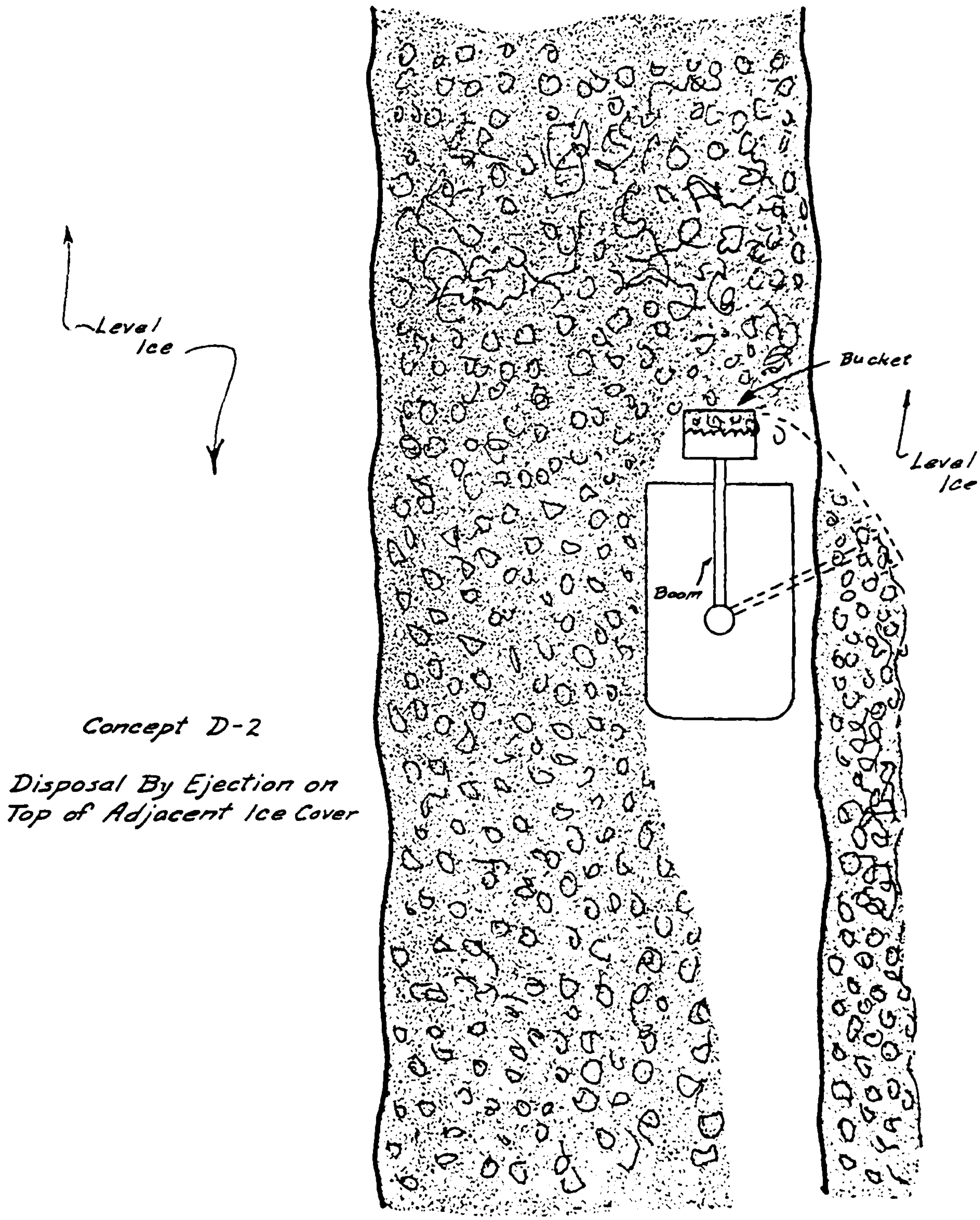
Disposal By Ejection on Top of Adjacent Ice Cover

Turns in the St Marys River

DISPOSAL METHOD: Ejection on Top of Ice (D.2)

CONCEPT DESCRIPTION: Large buckets used to pick up brash ice and deposit on top of ice.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Bucket would pick up brash.	Bucket size and operation time would need to be estimated.	Bucket size and operation time would need to be estimated.
TRANSFER	Bucket filled with brash ice would release its load on to ice cover.	Transfer time would need to be determined.	Transfer time would need to be determined.
STORAGE	Ice stored on top of unbroken ice cover.	The unborken ice cover should remain intact when brash ice is dumped on top. Method for spreading brash ice on top of ice cover needs to be determined.	Adequate storage at the turns in the St. Marys River is not available. It is feared that the thickened ice sheet may break off and become a hazard to navigation.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of large buckets mounted on ship.	This system may be required to make occasional stops to pick up and deposit ice.	No foreseeable problems.
CONCLUSION		Rejected. This system is not continuous and does not move with the flow of traffic.	Rejected. Ice cover cannot support required ice storage.



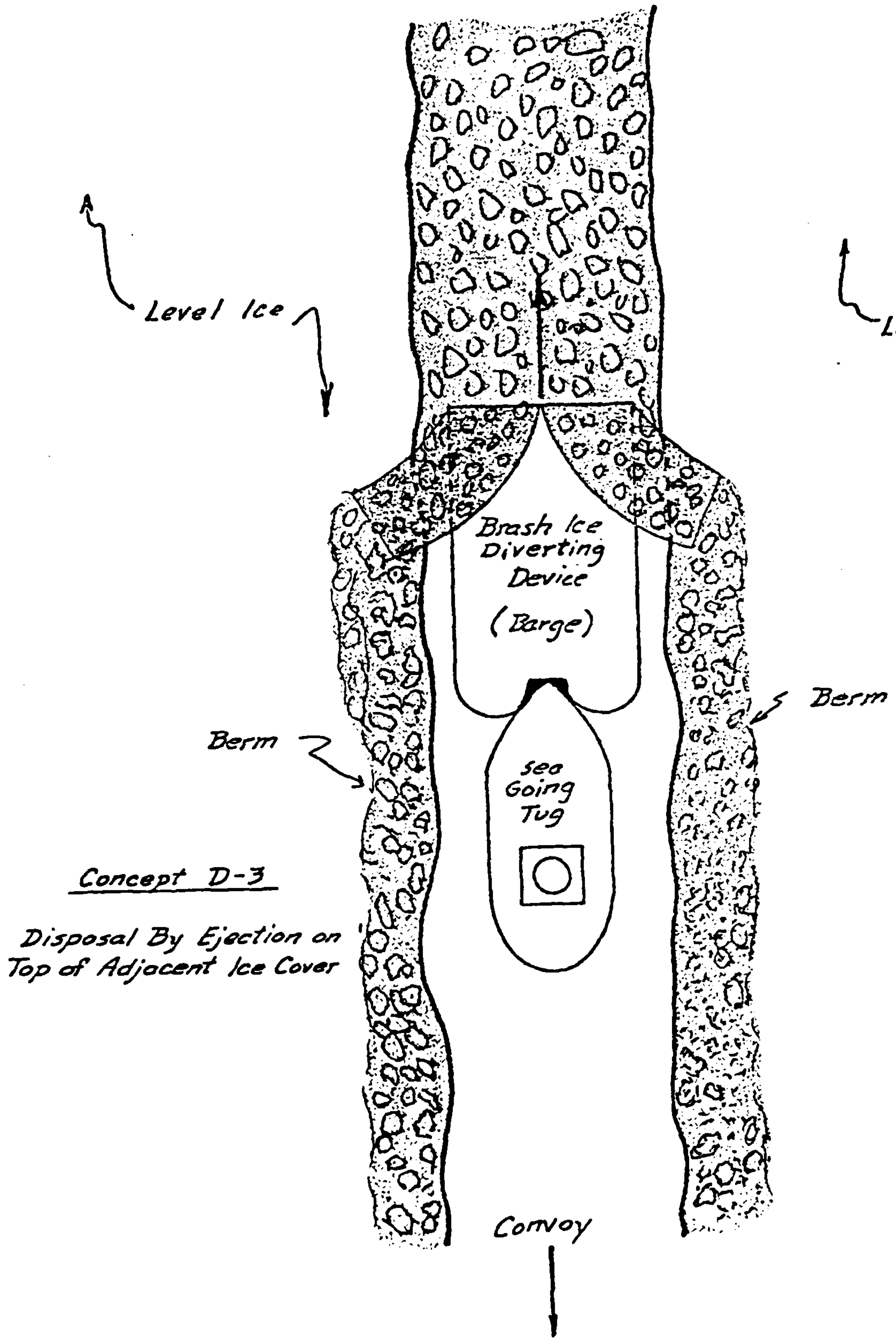
Concept D-2

Disposal By Ejection on Top of Adjacent Ice Cover

DISPOSAL METHOD: Ejection on Top of Ice (D.3)

CONCEPT DESCRIPTION: A bow mounted diverter would displace brash on top of the ice.

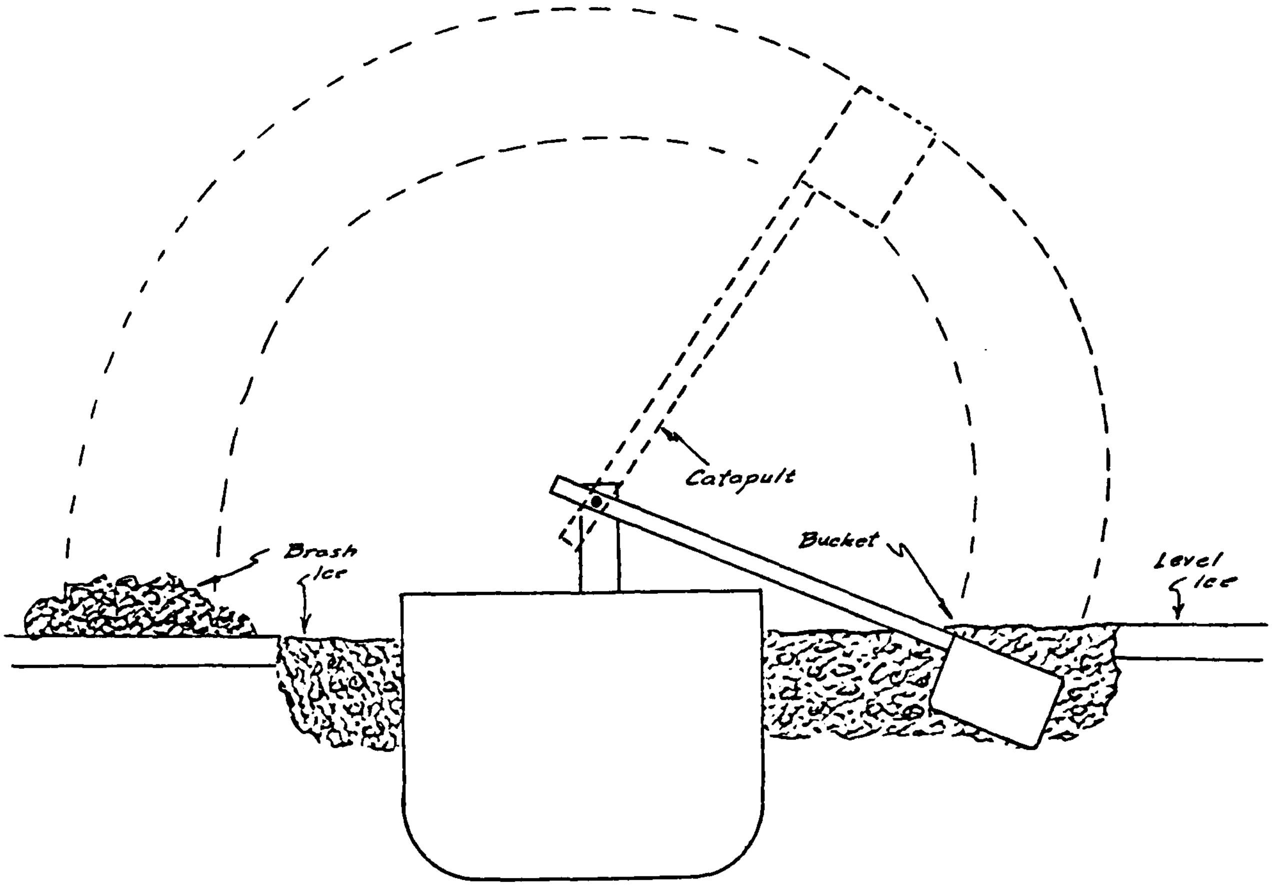
FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Bow mounted diverter would break the ice.	Icebreaking problems must be resolved in the design.	Icebreaking problems must be resolved in the design.
RECOVERY	Bow mounted diverter would lift broken ice.	Size and shape of the diverter would determine recovery rate. Side forces would require side thrusters.	Size and shape of the diverter would determine recovery rate. Side forces would require side thrusters.
TRANSFER	Diverter would transfer brash ice to top ice cover.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	Storage on top of ice sheet.	The unbroken ice cover should remain intact when brash ice is dumped on top. Method for spreading brash ice on top of ice cover needs to be determined.	Adequate storage at the turns in the St. Marys River is not available. It is feared that the thickened ice sheet may break off and become a hazard to navigation.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of bow mounted diverter which would displace brash ice on top of ice sheet.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Brash ice may break ice cover when stored on top.	Rejected. Ice cover cannot support required ice storage.


Level Ice
Level Ice
Brash Ice
Diverting
Device
(Barge)
Berm
Berm
Sea
Going
Tug
Concept D-3
Disposal By Ejection on
Top of Adjacent Ice Cover
Convoy

DISPOSAL METHOD: Ejection on Top of Ice (D.4)

CONCEPT DESCRIPTION: A catapult bucket device would pick up brash ice and hurl it onto the ice cover.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Bucket would break ice.	Icebreaking problems must be resolved in the design.	Icebreaking problems must be resolved in the design.
RECOVERY	Bucket would collect brash ice.	Size and shape of the bucket would determine recovery rate.	Size and shape of the bucket would determine recovery rate.
TRANSFER	Bucket on end of a catapult would have its load thrown onto the ice sheet.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	Storage on top of ice sheet.	The unbroken ice cover should remain intact when brash ice is dumped on top. Method for spreading brash ice on top of ice cover needs to be determined.	Adequate storage at the turns in the St. Marys River is not available. It is feared that the thickened ice sheet may break off and become a hazard to navigation.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	The system consists of a catapult bucket device mounted on a ship.	This system may not be able to travel with the flow of commercial traffic.	No foreseeable problems.
CONCLUSION		Rejected. This system is not continuous and may not be able to travel with the flow of traffic.	Rejected. Ice cover cannot support required ice storage.



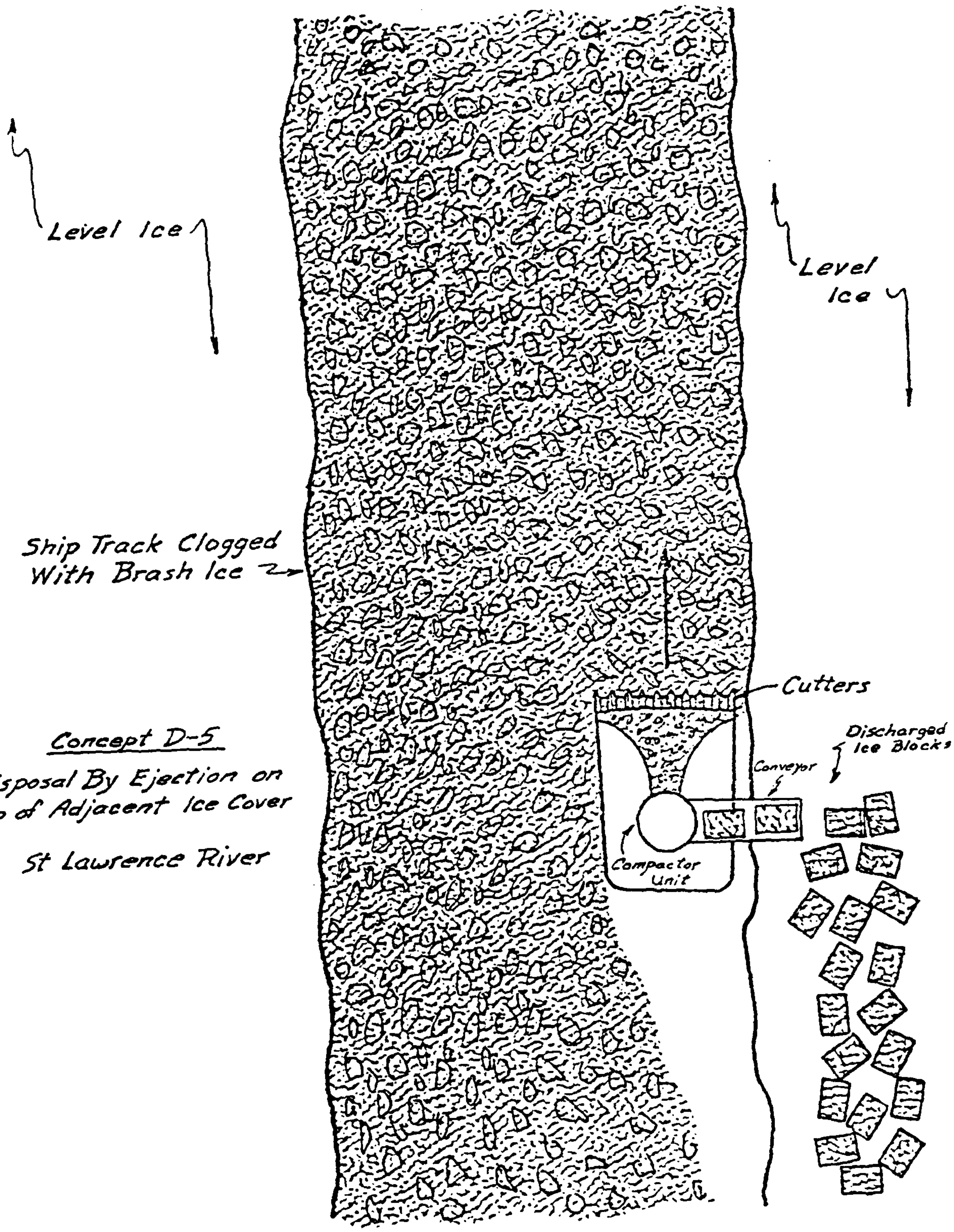
Concept D-4

Disposal By Ejection on Top of Adjacent Ice Cover

DISPOSAL METHOD: Ejection on Top of Ice (D.5)

CONCEPT DESCRIPTION: Brash ice gathered by slurry pump, frozen into blocks and placed onto ice cover.

FUNCTION	METHOD	ST. LAWRENCE RIVER *FUNCTIONAL REQUIREMENT EVALUATION*	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when the thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Broken ice is fed into compactor where it is formed into solid block.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
TRANSFER	Solid block of ice is placed on top of ice sheet via conveyor belt.	Accumulated brash ice on top of ice cover may cause problems during spring breakup.	Accumulated brash ice on top of ice cover may cause problems during spring breakup.
STORAGE	Ice blocks stored on top of ice cover.	The unbroken ice cover should remain intact when brash ice is dumped on top. Method for spreading brash ice on top of ice cover needs to be determined.	Adequate storage at the turns in the St. Marys River is not available. It is feared that the thickened ice sheet may break off and become a hazard to navigation.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	This system consists of an ice cutter, slurry pump, and ice compactor.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Brash ice compactor would need to be designed and evaluated. Compaction process is an unnecessary operation that requires additional energy.	Rejected. Ice cover cannot support required ice storage as well as compactor problems.



Concept D-5

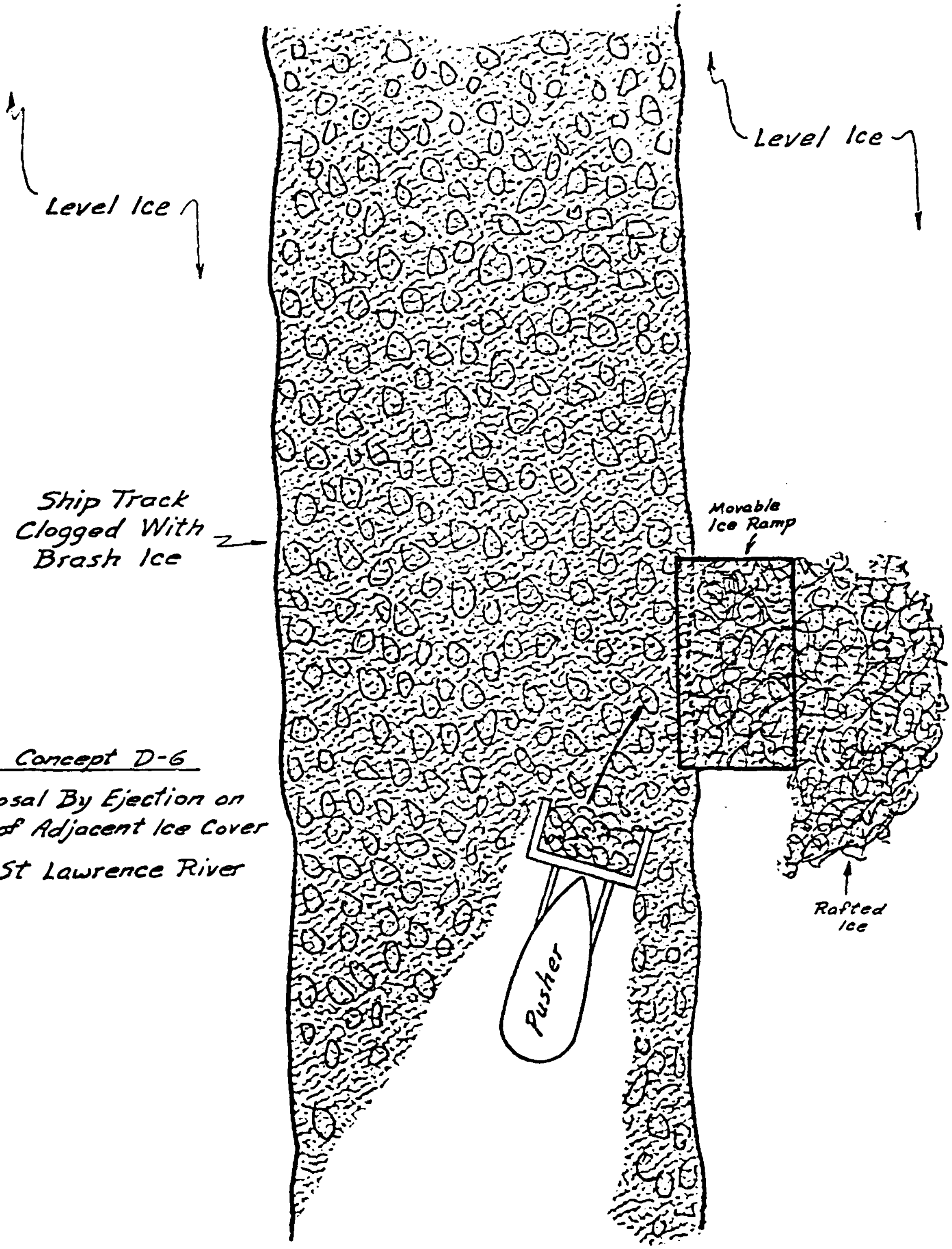
Disposal By Ejection on Top of Adjacent Ice Cover

St Lawrence River

DISPOSAL METHOD: Ejection on Top of Ice Cover (D.6)

CONCEPT DESCRIPTION: A movable ramp would be positioned next to ice cover. A pusher craft would then push the ice up the ramp onto the ice cover.

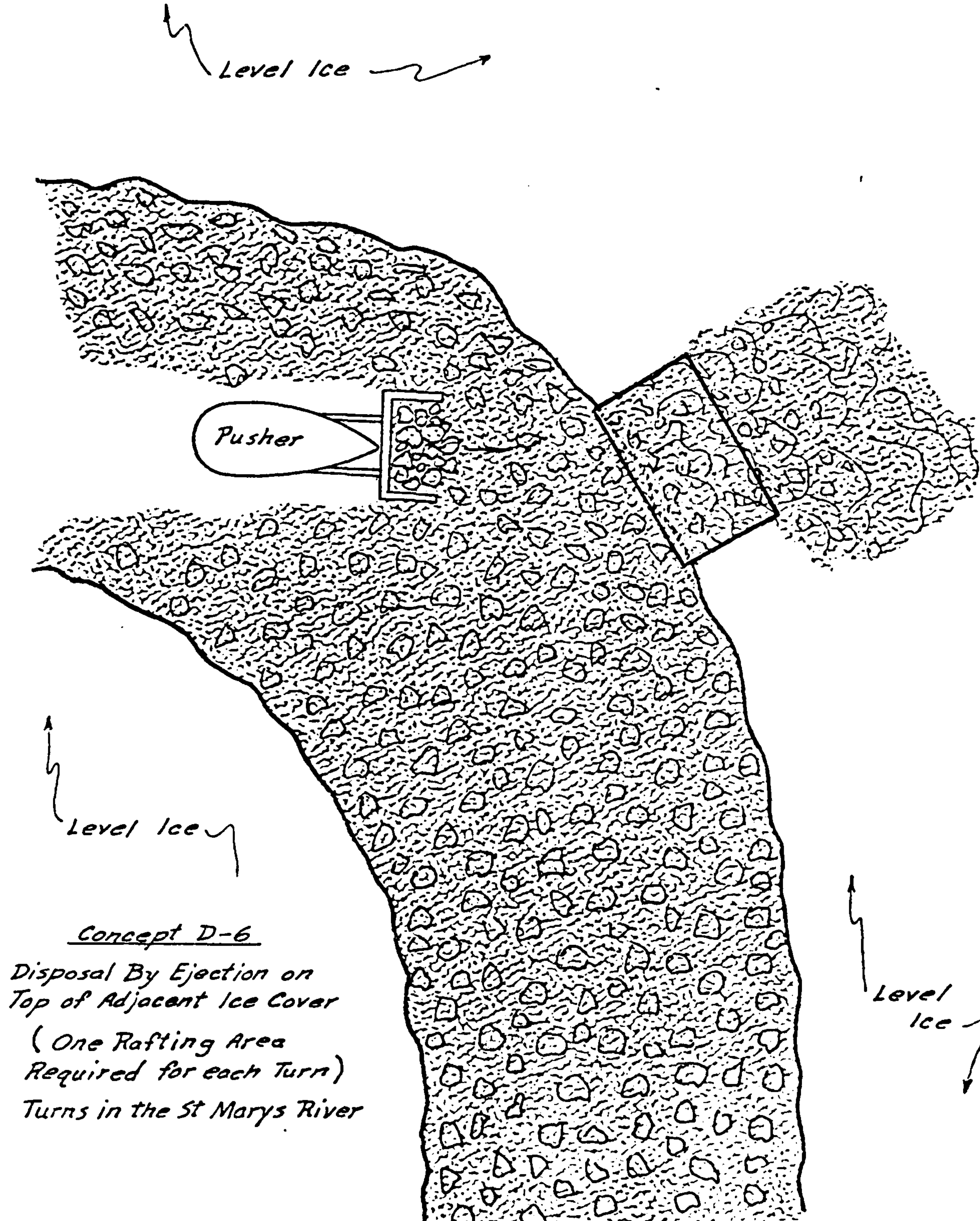
FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Bow of pusher craft would be used to break and move the ice.	Icebreaking problems must be resolved in the design.	Icebreaking problems must be resolved in the design.
RECOVERY	The broken ice would be pushed onto a ramp.	Size of ramp would determine recovery rate.	Size of ramp would determine recovery rate.
TRANSFER	The brash ice would be transferred to the ice cover via a ramp.	Accumulated brash ice on top of ice cover may cause problems during spring breakup.	Accumulated brash ice on top of ice cover may cause problems during spring breakup.
STORAGE	Brash ice would be stored on top of ice cover.	The unbroken ice cover should remain intact when brash ice is dumped on top. Method for spreading brash ice on top of ice cover needs to be determined.	Adequate storage at the turns in the St. Marys River is not available. It is feared that the thickened ice sheet may break off and become a hazard to navigation.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	This system consists of a pusher craft and a movable ramp.	This system would not travel with the flow of commercial traffic.	No foreseeable problems.
CONCLUSION		Rejected. This system does not operate continuously and would not travel with the flow of traffic.	Rejected. Ice cover cannot support required ice storage.



Concept D-6

Disposal By Ejection on Top of Adjacent Ice Cover

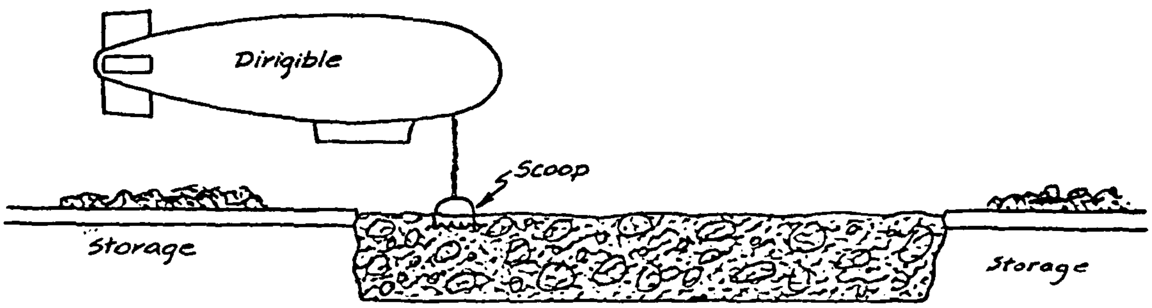
St Lawrence River


Level Ice
Pusher
Level Ice
Level Ice
Concept D-6
Disposal By Ejection on Top of Adjacent Ice Cover
(One Rafting Area Required for each Turn)
Turns in the St Marys River

DISPOSAL METHOD: Ejection on Top of Ice (D.7)

CONCEPT DESCRIPTION: A dirigible scoops up brash ice and then deposits it on the ice cover.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Scoop would be required to break ice.	Possible icing problems which must be resolved in design.	Possible icing problems which must be resolved in design.
RECOVERY	Scoop would be lowered from dirigible to pick up a load of brash ice.	Scooping process is not continuous and probably very time consuming.	Scooping process is not continuous and probably very time consuming.
TRANSFER	Dirigible would transfer ice to ice cover.	Method of transfer would need to ensure integrity of ice cover.	Method of transfer would need to ensure integrity of ice cover.
STORAGE	Brash ice would be stored on top of ice cover.	The unbroken ice cover should remain intact when brash ice is dumped on top. Method for spreading brash ice on top of ice cover needs to be determined.	Adequate storage at the turns in the St. Marys River is not available. It is feared that the thickened ice sheet may break off and become a hazard to navigation.
ULTIMATE DISPOSAL	Melting by solar radiation, warm air temperatures, and warm water temperatures which may be accelerated by coal dusting.	No foreseeable problems.	No foreseeable problems.
LOGISTICS	This system consists of a scoop attached to a dirigible and a brash ice storage area.	Special training for dirigible operation is required. Maintenance of dirigible may also require specialized training.	Special training for dirigible operation is required. Maintenance of dirigible may also require specialized training.
CONCLUSION		Rejected. Special equipment and training required for this system; therefore, logistics requirements not met.	Rejected. Ice cover cannot support required ice storage.



Note:
Dirigible Scoops up Ice
and Deposits on Both Banks

Concept D-7

Disposal By Ejection on top of
Adjacent Ice Cover

DISPOSAL METHOD: Melting (E.1)

CONCEPT DESCRIPTION: Utilize waste heat from nearby factories and power plants

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Not required.	Not required	Not required
RECOVERY	Heat would be added to river water such that brash ice growth would not reach thickness that would hinder navigation.	The amount of waste heat required to minimize brash ice growth is on the order of 1.3×10^{12} BTU's. It is highly unlikely that waste heat of the magnitude is available.	The amount of waste heat required to minimize brash ice growth is on the order of 27.2×10^{9} BTU's. It is highly unlikely that waste heat of this order of magnitude is available.
TRANSFER	Not required.	Not Required	Not required.
STORAGE	Not required.	Not required	Not required
ULTIMATE DISPOSAL	Not required	Not required	Not required
LOGISTICS	The system consists of melting brash ice utilizing waste heat from nearby factories and power plants.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. The waste heat energy required to melt the required volume of brash ice is probably not available.	Rejected. The waste heat energy required to melt the required volume of brash ice is probably not available.

DISPOSAL METHOD: Melting (E.2)

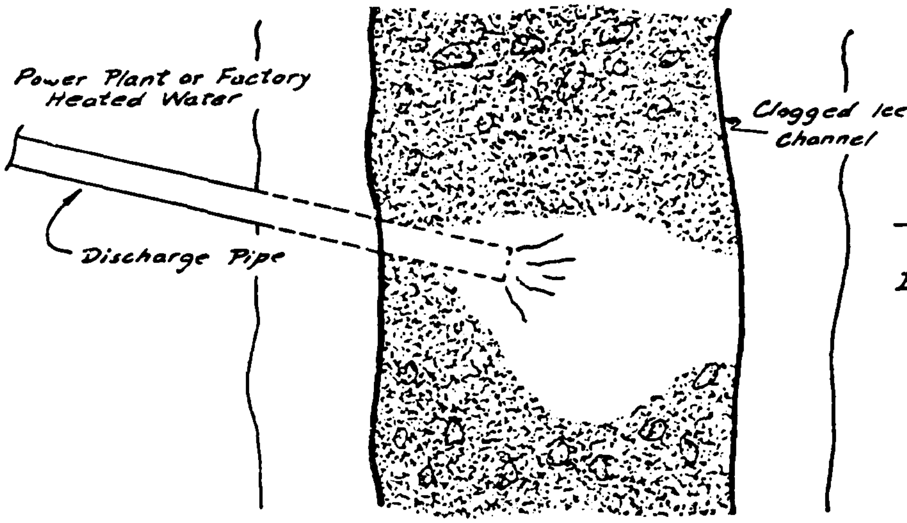
CONCEPT DESCRIPTION: Use Hydroelectric Power to Warm Water

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Not required	Not required.	Not required.
RECOVERY	Power from a hydroelectric power plant would be used to sufficiently heat the water to minimize brash ice growth.	The amount of power required is on the order of 324 MW over a 48 day period. It is highly unlikely that electric power of this magnitude could be diverted from existing power plants to melt brash ice.	The amount of power required is on the order of 5.0 MW over a 66 day period. It is highly unlikely that electric power of this magnitude could be diverted from existing power plants to melt brash ice.
TRANSFER	Not required.	Not required.	Not required.
STORAGE	Not required.	Not required.	Not required.
ULTIMATE DISPOSAL	Not required.	Not required.	Not required.
LOGISTICS	The system consists of melting brash ice utilizing heat generated from a hydroelectric power plant.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Energy required to melt the required volume of brash ice is not available.	Rejected. Energy required to melt the required volume of brash ice is not available.

DISPOSAL METHOD: Melting (E.3)

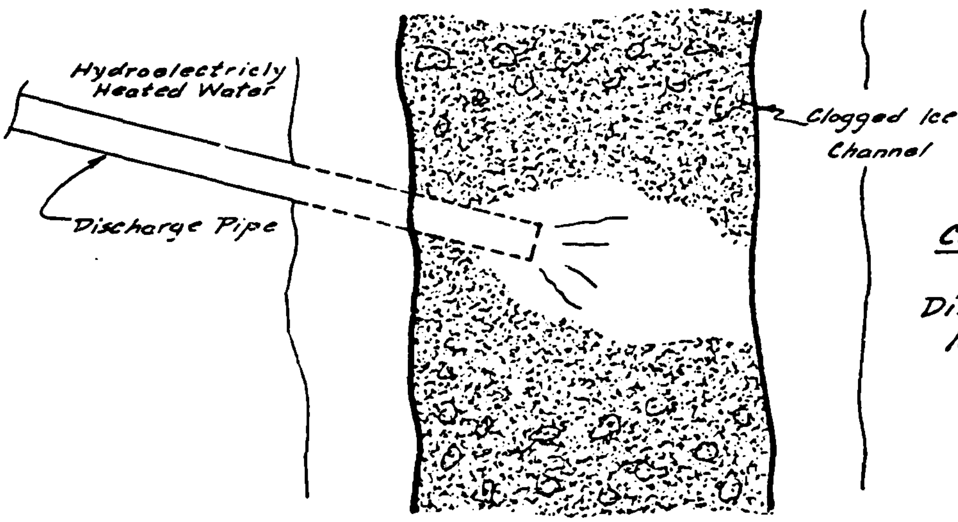
CONCEPT DESCRIPTION: Use fossil fuels to heat water.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses appraoch limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Not required.	Not required.	Not required.
RECOVERY	Heat from oil or coal burning systems will heat the river water to minimize brash ice growth.	The amount of fuel required to melt brash ice is approximately 9.5 million gallons. Fuel requirements may be excessive.	The amount of fuel required to melt brash ice is approximately 200,000 gallons. Fuel requirements may be excessive.
TRANSFER	Not required.	Not required.	Not required.
STORAGE	Not required.	Not required.	Not required.
ULTIMATE DISPOSAL	Not required.	Not required.	Not required.
LOGISTICS	The system consists of melting brash ice utilizing fossil fuels to heat the water.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Fuel requirements are excessive.	Rejected. Fuel requirements are excessive.



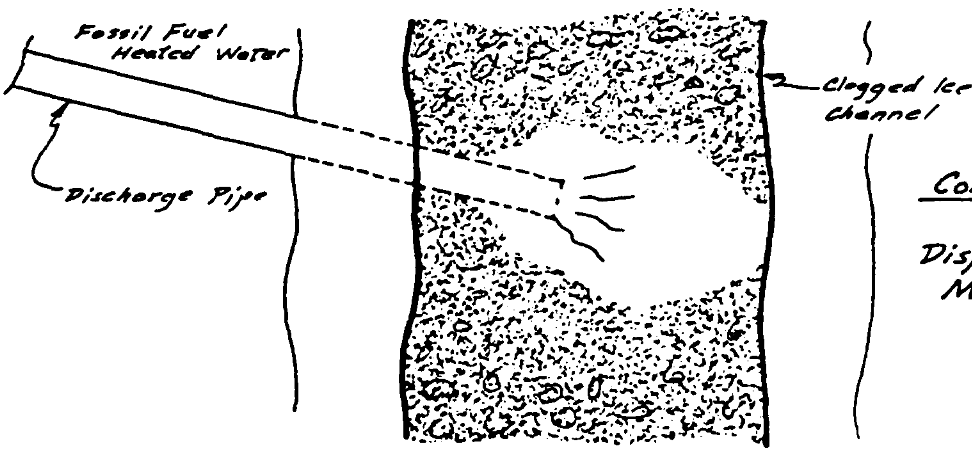
Concept E-1

Disposal By Melting



Concept E-2

Disposal By Melting



Concept E-3

Disposal By Melting

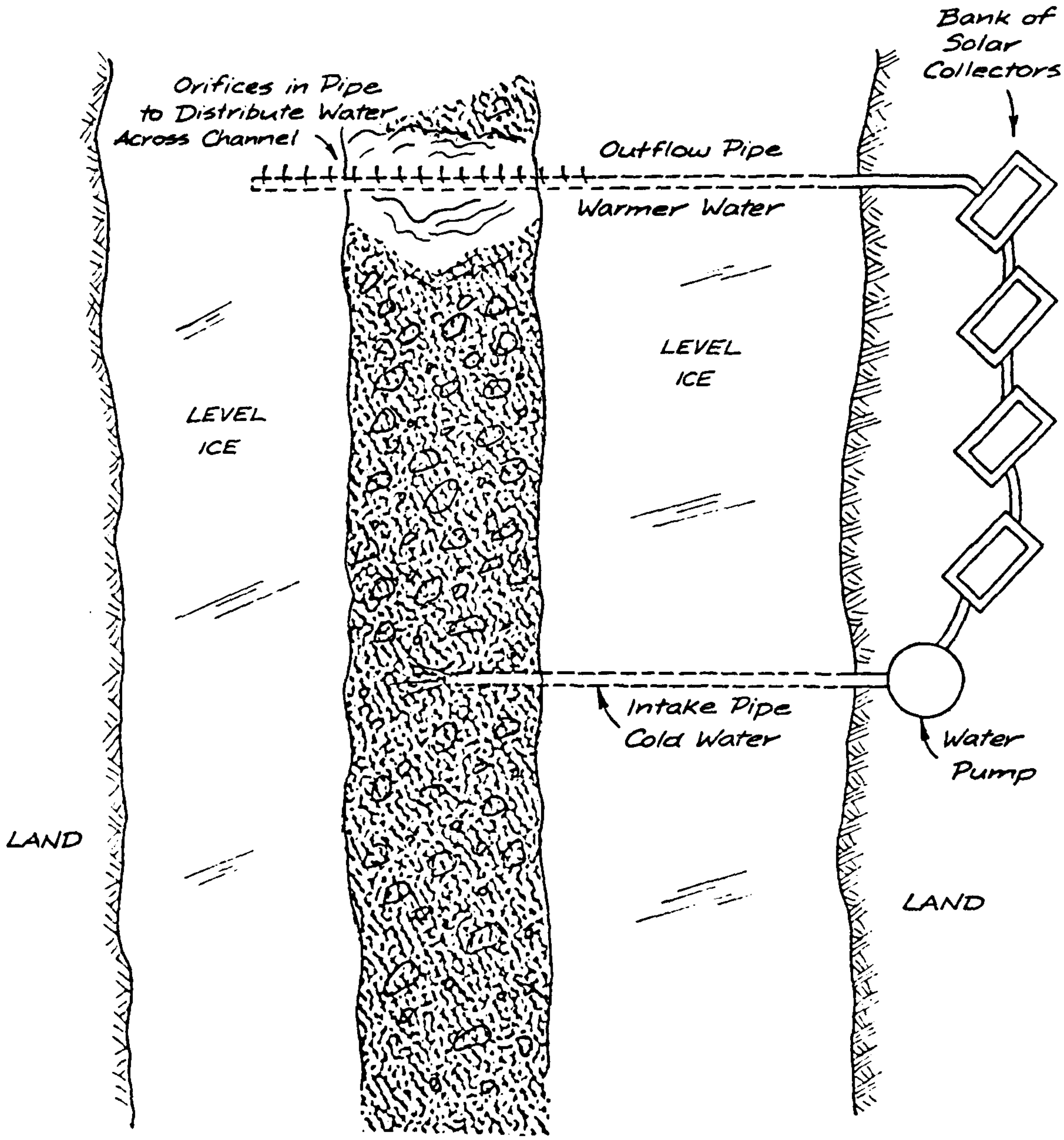
DISPOSAL METHOD: Melting (E.4)

CONCEPT DESCRIPTION: Construct solar collector to heat water.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Not required.	Not required.	Not required.
RECOVERY	Energy from solar collectors would be used to heat the water to minimize brash ice growth.	To melt the required volume of brash ice, a solar collector system would require a minimum of 2.29 square miles of collector surface area.	To melt the required volume of brash ice, a solar collector system would require a minimum of 0.036 square miles of collector surface area.
TRANSFER	Not required.	Not required.	Not required.
STORAGE	Not required.	Not required.	Not required.
ULTIMATE DISPOSAL	Not required.	Not required.	Not required.
LOGISTICS	The system consists of a number of solar collector systems that would heat the water and melt the brash ice.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Accepted.	Accepted.

Concept E-4

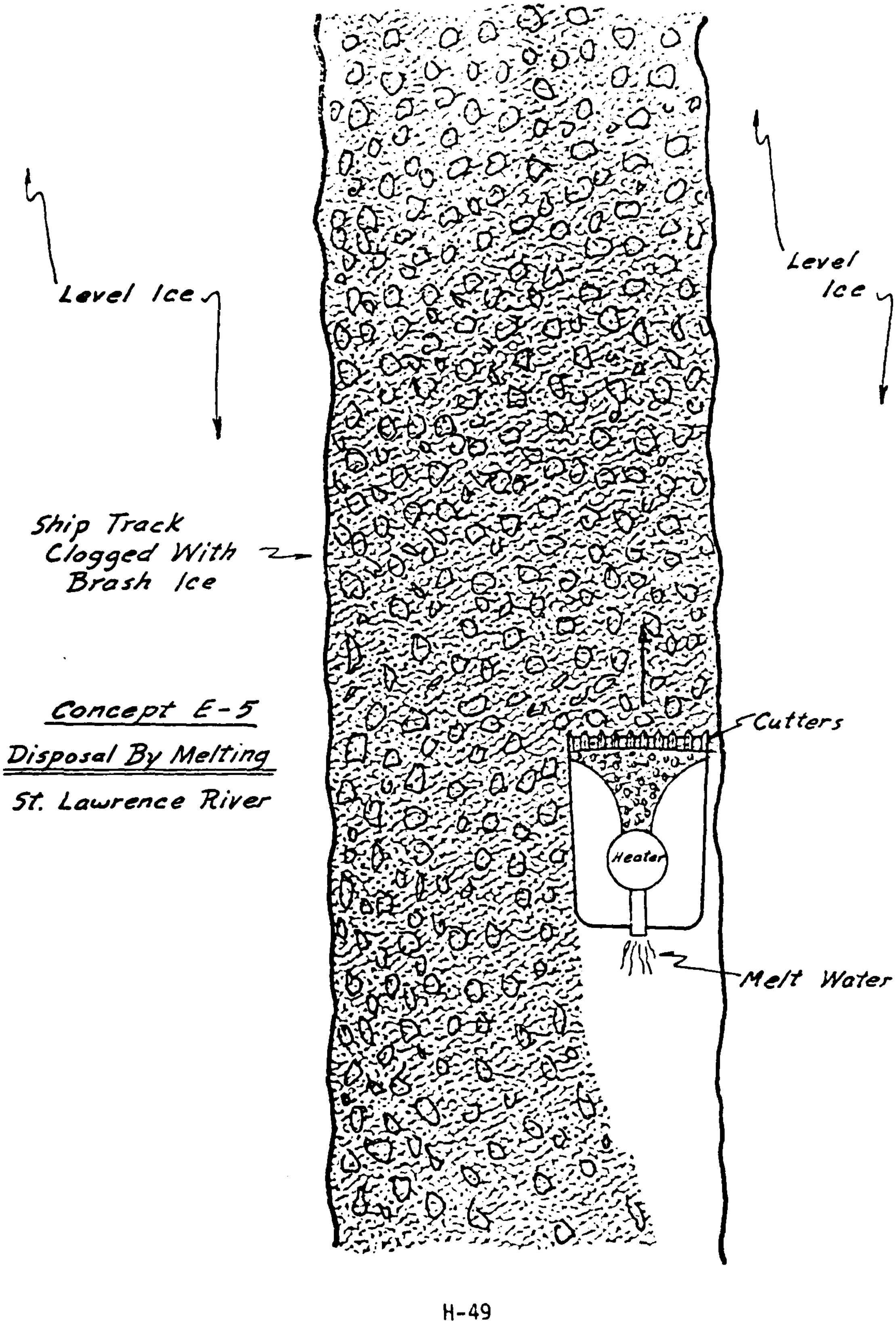
Disposal By Melting

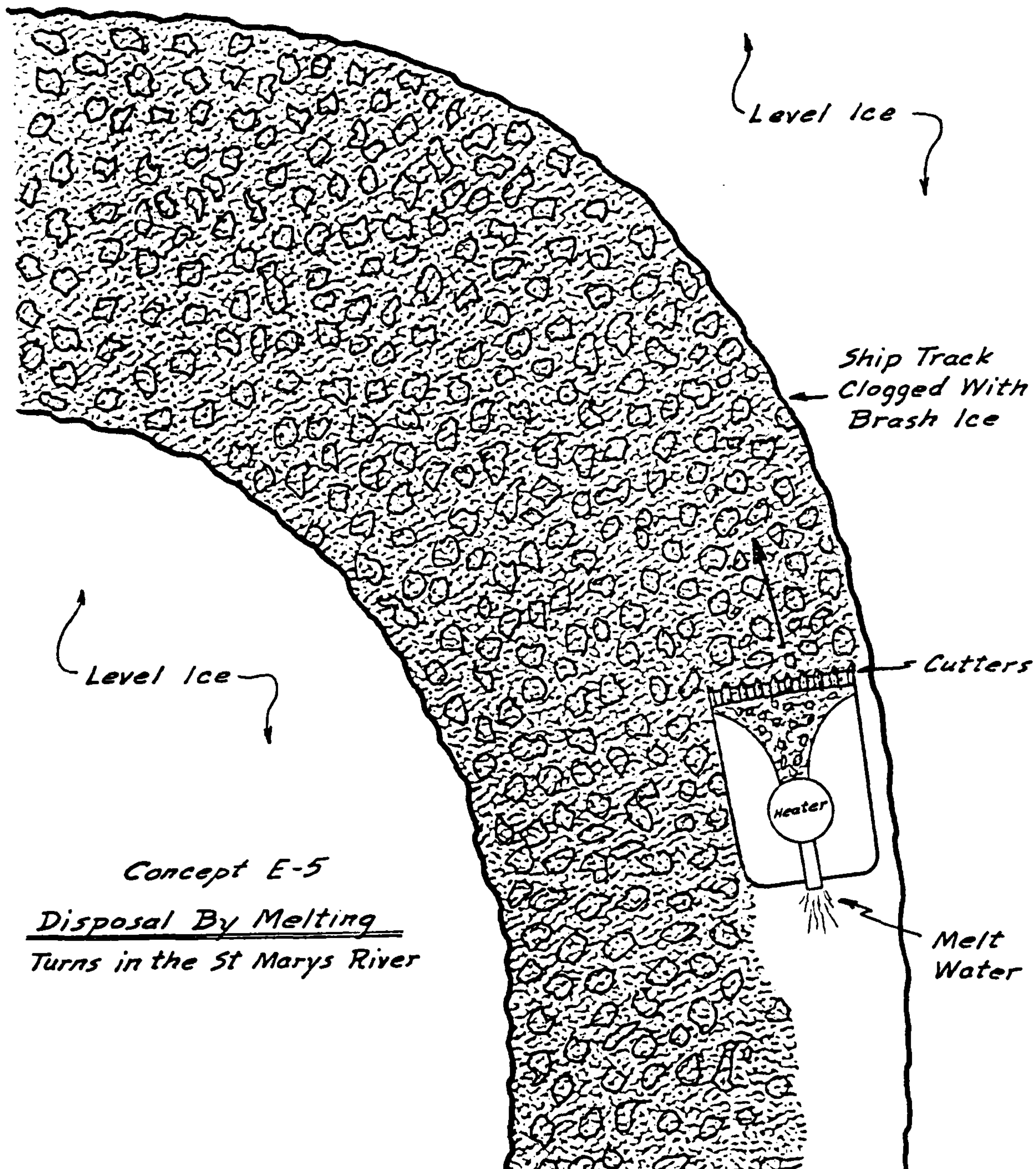


DISPOSAL METHOD: Melting (E.5)

CONCEPT DESCRIPTION: Ship mounted burners would melt brash ice.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Level ice, refrozen ice, and large unconsolidated brash ice pieces are to be reduced in size by saws, cutters, or grinders.	Possible icing problems which must be resolved in the design.	Possible icing problems which must be resolved in the design.
RECOVERY	Broken ice is pumped or conveyed on board ship where heat is added to brash ice.	High powered, maneuverable vessel is required. Recovery is continuous. The amount of fuel required to melt the brash ice may be excessive.	High powered, maneuverable vessel is required. Recovery is continuous. The amount of fuel required to melt the brash ice may be excessive.
TRANSFER	The heated brash and melt water are pumped back into the river.	Possible icing problems during operation and between operating shifts must be resolved in the design.	Possible icing problems during operation and between operating shifts must be resolved in the design.
STORAGE	Not required.	Not required.	Not required.
ULTIMATE DISPOSAL	Not required.	Not required.	Not required.
LOGISTICS	The system consists of ship mounted burners, ice cutters, and a slurry pump.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Fuel requirements are excessive.	Rejected. Fuel requirements are excessive.


Level Ice
Level Ice
Ship Track Clogged With Brash Ice
Concept E-5
Disposal By Melting
St. Lawrence River
Cutters
Heater
Melt Water



Concept E-5

Disposal By Melting

Turns in the St Marys River

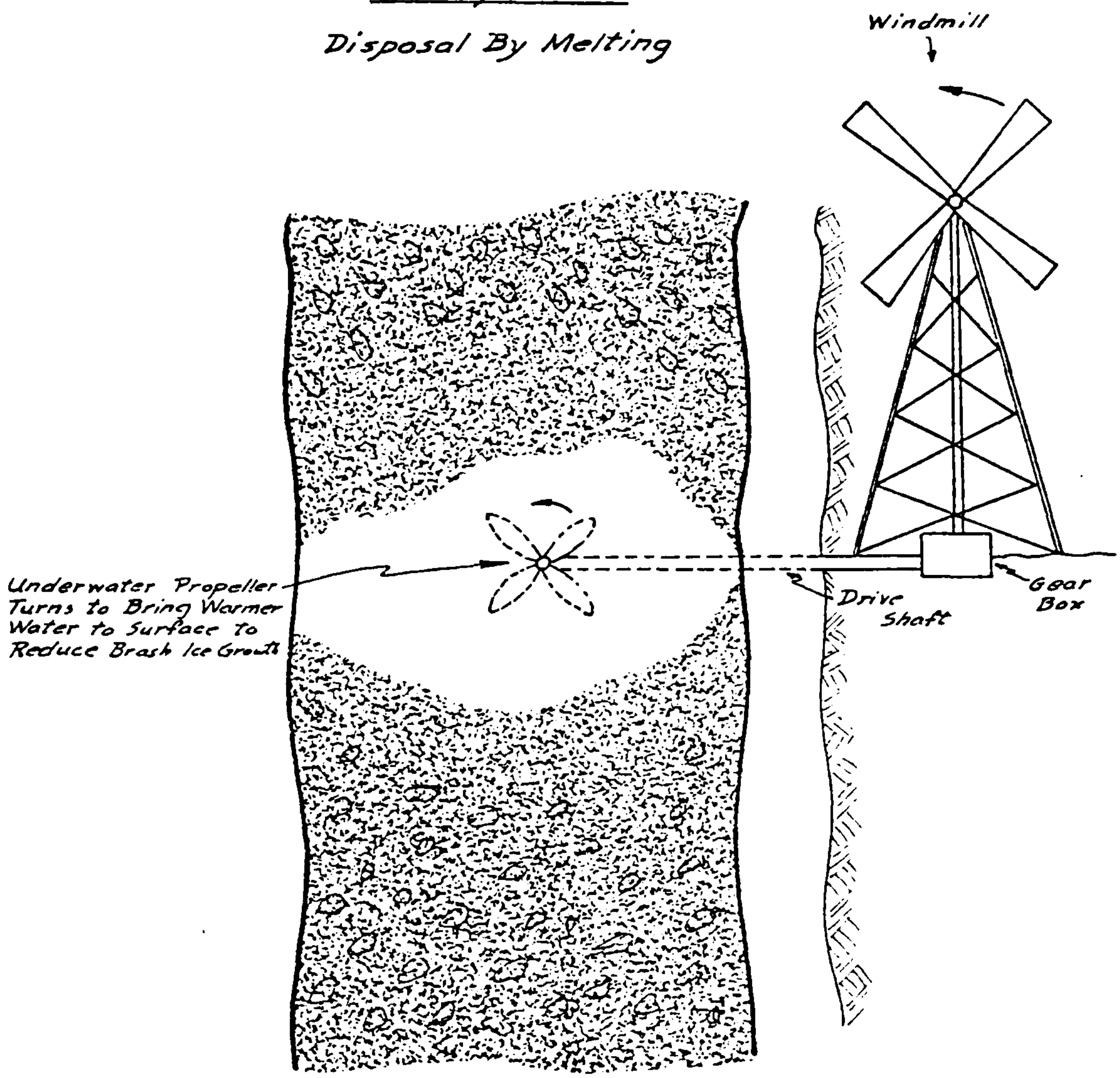
DISPOSAL METHOD: Melting (E.6)

CONCEPT DESCRIPTION: Utilize windmill driven impeller to circulate water to minimize brash ice growth rate.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Not required.	Not required.	Not required.
RECOVERY	Energy from the wind would be used to power underwater propellers to mix water at the bottom with the brash ice at the top.	Possible problems if water temperature gradient does not exist. Circulation may actually promote brash ice growth.	Possible problems if water temperature gradient does not exist. Circulation may actually promote brash ice growth.
TRANSFER	Not required.	Not required.	Not required.
STORAGE	Not required.	Not required.	Not required.
ULTIMATE DISPOSAL	Not required.	Not required.	Not required.
LOGISTICS	The system consists of a windmill driven impeller used to circulate the water and minimize brash ice growth.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Rejected. Water temperature gradient does not exist in St. Lawrence River.	Rejected. Water temperature gradient does not exist in St. Marys River.

Concept E-6

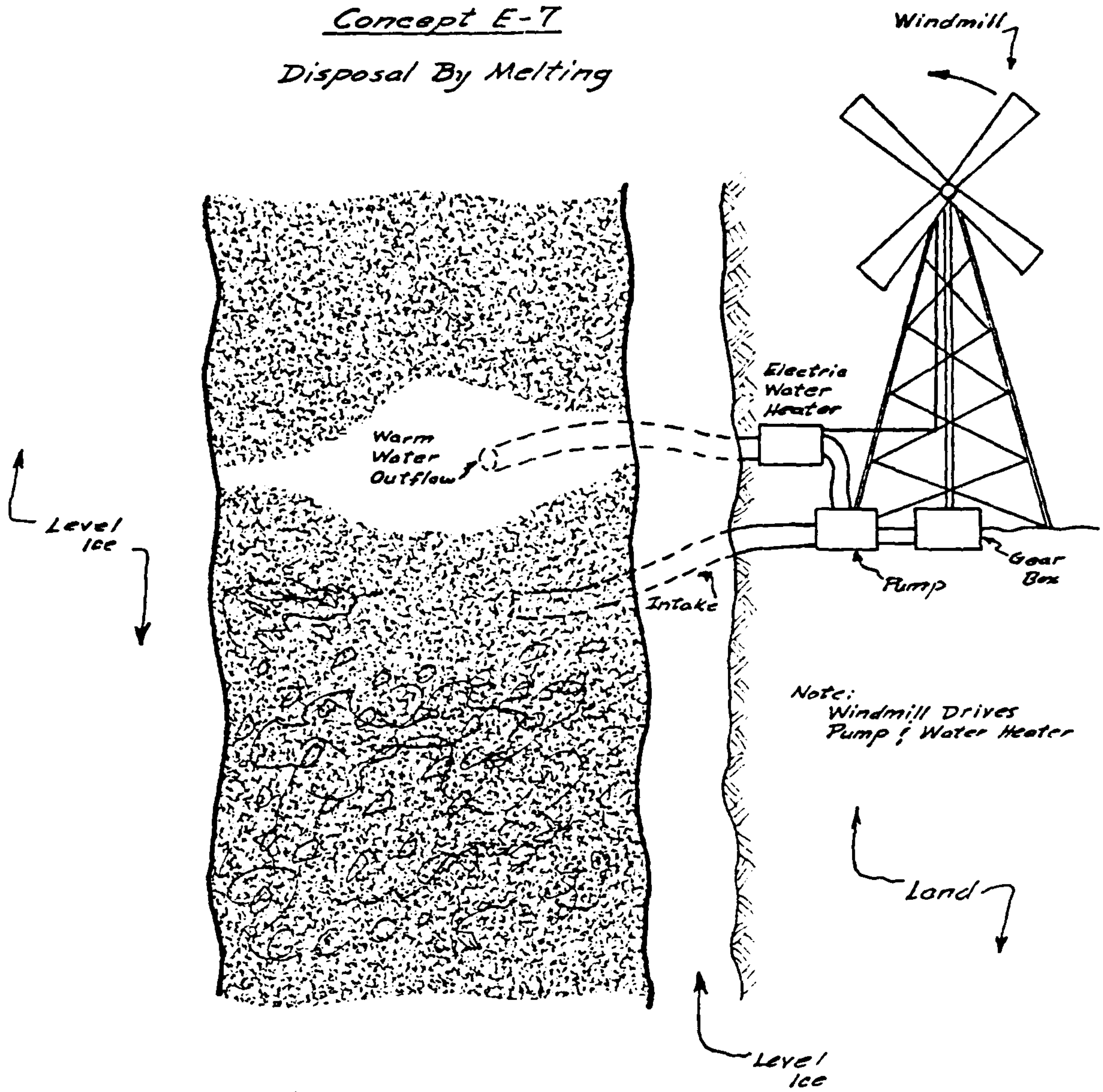
Disposal By Melting



DISPOSAL METHOD: *Melting (E.7)*

CONCEPT DESCRIPTION: Utilize windmill driven generator that would produce electricity to the heat the water.

FUNCTION	METHOD	ST. LAWRENCE RIVER FUNCTIONAL REQUIREMENT EVALUATION	ST. MARYS RIVER FUNCTIONAL REQUIREMENT EVALUATION
DETECTION	Record ice thickness at various locations along the river.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.	Record ice thickness at various locations along the river and when thicknesses approach limiting thickness deploy channel clearing equipment. No foreseeable problems.
ICEBREAKING	Not required.	Not required.	Not required.
RECOVERY	Wind energy would be converted to heat and used to heat the water and minimize brash ice growth.	To melt the required volume of brash ice, a minimum of 32,400 windmills rated at 10 KW each would be required.	To melt the required volume of brash ice, a minimum of 500 windmills rated at 10 KW each would be required.
TRANSFER	Not required.	Not required.	Not required.
STORAGE	Not required.	Not required.	Not required.
ULTIMATE DISPOSAL	Not required.	Not required.	Not required.
LOGISTICS	The system consists of a number of windmill driven generators that would produce electricity to heat the water.	No foreseeable problems.	No foreseeable problems.
CONCLUSION		Accepted.	Accepted.


Concept E-7
Disposal By Melting
Windmill
Electric
Water
Heater
Warm
Water
Outflow
Level
Ice
Intake
Pump
Gear
Box
Note:
Windmill Drives
Pump & Water Heater
Land
Level
Ice

APPENDIX I

THE ARCHIMEDEAN SCREW TRACTOR

APPENDIX I

THE ARCHIMEDEAN SCREW TRACTOR

One amphibious vehicle which is judged to have great potential as a transport vehicle in the arctic is the Archimedean Screw Vehicle (ASV). ARCTEC, Incorporated has completed several projects over the last few years related to the development of an amphibious version of this vehicle for Mitsui Engineering and Shipbuilding Company, Ltd., of Tokyo, Japan. In order to achieve an amphibious capability, the payload of this vehicle is primarily in the form of a drawbar pull rather than an onboard cargo carrying capacity. Hence, the vehicle was named the Archimedean Screw Tractor (AST). When used in conjunction with sled-barges for carrying the payload, AST/Sled-Barge systems can provide an unequalled year-round transport capability in the arctic.

In the development of the Archimedean Screw Tractor, Mitsui, starting in 1976, initially investigated the performance of Archimedean screws in ARCTEC's Ice Model Basin. This test program was followed by field tests of small Archimedean Screw Tractor models in which five combinations of screw blade height and helix angle were investigated. The next phase of the development program consisted of maneuvering tests of Archimedean Screw Tractor models conducted at ARCTEC's Ice Model Basin. The fourth step in Mitsui's AST development program consisted of the construction and field testing of an experimental AST designated the AST-001 in late 1978 and early 1979. This gasoline engine powered aluminum vehicle, having a weight of 1,570 kg and operated by a crew of two, clearly demonstrated the capability of the AST to transit open water, broken ice fields, on ice, on snow, over pressure ridges, and in transition between ice and water. When operated on ice, the AST-001 achieved a maximum drawbar pull of 1,740 kg, or roughly 110% of its weight. In open water the AST-001 achieved a bollard pull of 250 kg, or about 14 lbs per installed horsepower.

The success of the AST-001 trials led to the design of a 10 ton prototype AST-002. The principal characteristics are summarized in Table 1 and the general arrangement and layout of AST-002 are shown in Figure 1. AST-002 was constructed by MES and tested in Northern Hokkaido, Japan. The trials of AST-002 were witnessed by Mr. J. Coburn of ARCTEC and Mr. J. Rymes, PE., under contract to Phillips Petroleum.

The trials were an unqualified success. The larger AST-002 was more stable than the AST-001, stability having been the only potential problem with 001. 002 developed a maximum drawbar pull of 10 tons, as predicted, and produced an open water bollard thrust of 1 ton. Speed was as predicted--6 knots on solid ice, 4 knots in open water, and 3 to 4 knots while breaking ice 12" to 18" thick.

The diesel-hydraulic drive has proven to be 100% reliable, delivering up to the maximum torque at all speeds. The flexibility, simplicity, and ease of control afforded by the hydraulic system have more than compensated for the incrementally higher cost and weight.

The rotors were designed to take a concentrated load of twice the total vehicle weight. A test section was fabricated, identical to the rotors as installed, and destructively tested (crushed). 23 tons produced a minor indentation. To date, there is no sign of wear or any other deterioration in either 001's or 002's rotors.

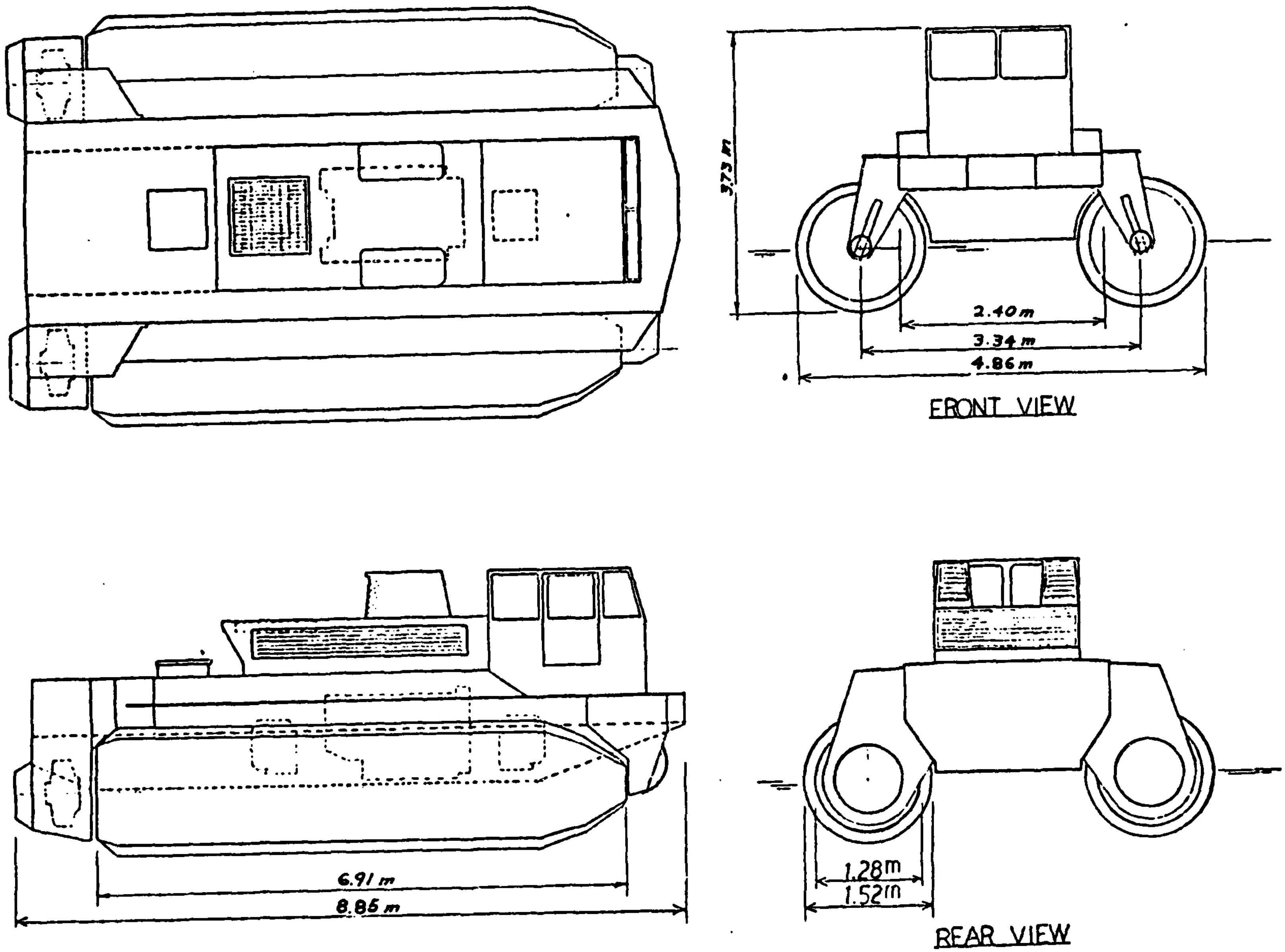


Figure 1. Sketch of Mitsui's AST 002

TABLE 1. PRINCIPAL CHARACTERISTICS OF MITSUI'S AST-002

TYPE	AMPHIBIOUS ARCHIMEDEAN SCREW
NO. OF CREW	5
WEIGHT	ABT. 10.3 TONS
MATERIAL	ALUMINIUM
RUNNING TIME	4 HRS
DIMMENSIONS LENGTH x BEAM x HEIGHT (OVERALL) ROTOR LENGTH x DRUM DIA. x BLADE HEIGHT	 8.85 x 4.86 x 3.73 m 6.91 x 1.52 x 0.12 m
DRAFT IN WATER	0.79 m
BLADE HELIX ANGLE	30 DEG.
NO. OF BLADES	2
SPEED ON ICE IN WATER	 NORMAL MODE MAX. 6.02 KNOTS @80RPM TRAVERSE MODE MAX. 12.38 KNOTS @80RPM MAX. 3.82 KNOTS @80RPM
ICE BREAKING CAPABILITY	ICE THICKNESS ABT. 40 CM SPEED ABT. 3.0 KNOTS @40RPM
BOLLARD PULL	ON ICE MAX. 10 TONS IN WATER MAX. 1 TON
ENGINE	AIR COOLED, 12 CYL. V-TYPE DIESEL MCO 305 PS/2300 RPM x 1 SET
TRANSMISSION	HYDRO-STATIC

APPENDIX J

WTGB RESISTANCE AND VOLUME CALCULATIONS
FOR PUSHING BRASH ICE

APPENDIX J

WTGB RESISTANCE AND VOLUME CALCULATIONS FOR PUSHING BRASH ICE

The volume of brash ice that the WTGB could push and the plow size were determined using the equation for resistance of the WTGB in brash ice without air bubblers from Reference [27].

$$\frac{R_H}{\rho_i \, g \, Bh^2} = 0.6 + 0.1 \left(\frac{V^2}{gh}\right) \tag{J.1}$$

where

R_H = the hull resistance in pounds

$\rho_i g$ = the weight density of ice in lbs/ft³

B = the waterline beam of the ship in feet

h = the thickness of the ice in feet

V = the speed of the ship in fps

g = the gravitational constant in ft/sec²

and the equation of resistance of a laker bow in brash ice [26]. The laker bow, with its high block coefficient and flat-sided sections, was used because the crushing effect and subsequent development of a berm in front of the ship would be much the same as a plow of a width equal to the beam of the bow. That equation is as follows:

$$\frac{R_P}{\rho_w g \, B_P h^2} = 1.05 + 2.10 \frac{V}{\sqrt{gh}} \tag{J.2}$$

where

R_P = the resistance of the plow in pounds

$\rho_w g$ = the weight density of fresh water

B_P = the width of the plow in feet

A design speed of 4 knots was chosen and resistance was calculated for a plow width equal to the waterline beam of the WTGB (33' - 9"), using: using:

$$R = R_P + \frac{R_H}{2} \qquad (J.3)$$

Only half the hull resistance was assumed since the plow would divert ice away from the hull. For this case and 4 feet of brash ice thickness,

$$R_P = 66{,}970 \text{ lbs}$$

$$R_H = 20{,}140 \text{ lbs}$$

$$R = 77{,}040 \text{ lbs.}$$

The available thrust at 4 knots and 2500 HP for the WTGB is 44,240 lbs from Reference [27]. The design conditions require operating in 31 to 48 inches of ice. Therefore, the size of the plow should be reduced so the ship can still make 4 knots in 4 feet of brash. The resistance of the plow calculated above, however, is for a fully developed berm. Reference [28] gives the ratio of maximum berm thickness to ice thickness as 6.44 for ϕ, the internal angle of friction, equal to 47°. Based on a 4 foot ice thickness, the plow would have to be almost 26 feet deep. Limiting the depth of the plow to 12 feet, the draft of the WTGB,reduces the area of the plow to below that required for 4 knots in 4 feet of brash ice, assuming a linear relationship between resistance and plow depth as there is with plow width.

The final plow dimensions are then 36.9 feet wide by 12 feet deep. The volume is calculated by:

$$V = 31.16\, B_P\, h^2 - 178\, h^3 \qquad (J.4)$$

based on a shear failure line on both sides of the plow at an angle of 45° - $\phi/2$ for ϕ = 47° [28] and an angle of response in water of α = 33°. Figure J.1 shows the volume calculated and the angles used. Since the volume is dependent on the thicknesses encountered, the average thickness encountered for the 66 days requiring removal in the severe winter design case was calculated. The volume associated with the average ice thickness will be used in the operational scenarios.

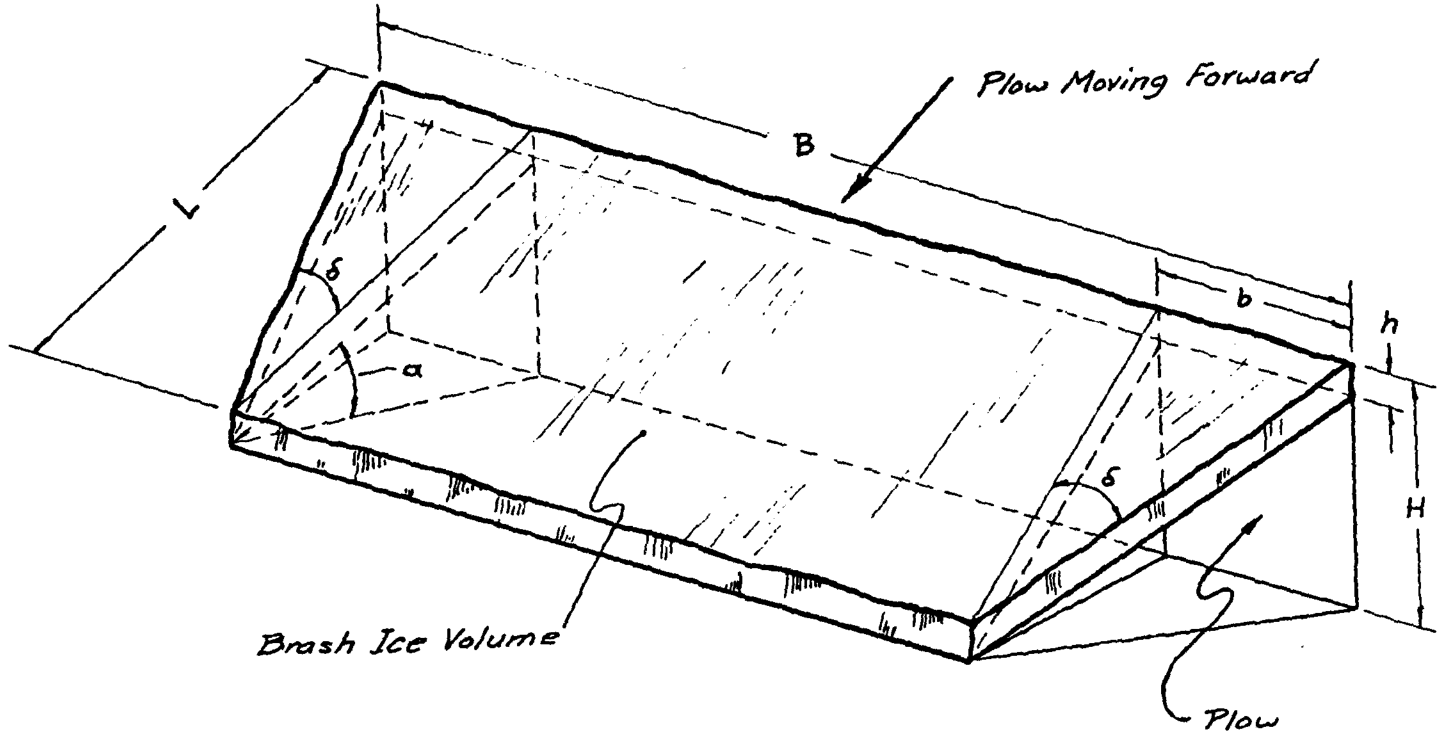


Figure J.1. Volume of Brash Ice Pushed by a Plow

ND

DATE